THE FORESEEABLE FUTURE

BY

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PREFACE

This book is called *The Foreseeable Future*, but a quick glance at its contents shows that it deals chiefly with the future of technology. The limitation is a reasonable consequence of the adjective. Technology is governed by scientific principles, some of which are understood, and there is accordingly a basis for prediction. Sociology has still to find its Newton, let alone its Planck, and prediction is guesswork.

I have supposed that developments which do not contradict known principles and which have an obvious utility will in fact be made, probably in the next hundred years. No doubt there will be discoveries which will transcend what now appear major impossibilities, but these are unpredictable, and so are the practical developments which will follow from them.

In some of what follows I have gone outside the studies of which I can claim any professional knowledge. For this rash act I ask the forgiveness of those into whose coverts I have trespassed. If some of the game I have reported exists only in my imagination, at least this kind of poaching does no harm to the rightful owners, while the onlooker may occasionally see something that is both unexpected and real.

G. T.

CAMBRIDGE
March 1955

CHAPTER I

INTRODUCTION

THE last three hundred years have been marked by an increase in man's power over his surroundings unexampled in any equal period of the past. One cannot help asking how long it will last. Will this rate of material progress, which seems to be steadily accelerating, continue faster and faster, will it level off to a steady and much slower advance, or will it end in a catastrophe and a dark age? The nearest historical parallel, and that a very incomplete one, is the invention of agriculture in the neolithic age. This led to a great increase in the populations which adopted it and to the foundation of cities, but written records do not go back far enough to tell us the difficulties which the men who began this innovation had to conquer or how they overcame them, and when it later spread it did so as an established mode of life. Perhaps a study of those North American tribes, who, when first reached by Europeans, were apparently beginning to cultivate maize on their own initiative, and with little if any contact with the developed civilization further south, might give one hints. One cannot help feeling that it was a slow process with many setbacks.

Our own problem could be attacked from at least two quite different sides. One could consider what further technical advances are likely and then see what reaction they are likely to have on people's lives, or

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The very rapid progress now going on is essentially based on scientific discovery. Up to about the year 1650 progress in technology was mostly due to uneducated people and proceeded slowly on a hit-or-miss basis. About the time of Galileo and Francis Bacon experiment became respectable for gentlemen, and the possibility of educated men interesting themselves in technology greatly increased. For example, magnetism was a relatively early branch of science and owed much of its progress to the interest in its use as an aid to the navigation of the oceans, then becoming of the greatest commercial and political importance. But only a part of the great improvement in technology in the seventeenth and eighteenth centuries was due to educated men or had more than an indirect connection with science. Watts indeed was an instrument-maker attached to the Natural Philosophy department of the University of Glasgow, and probably owed more inspiration to a model of the early Newcomen engine that he was asked to mend, than he did to his mother's kettle. But the science of heat gained more from the steam-engine than the steam-engine from it, till the nineteenth century was more than half over. Science favoured technology more by the attitude of mind which it encouraged in the governing classes than by the actual application of its discoveries. This was changed by the discovery of electric currents, and especially by Faraday's discovery of electro-magnetic induction in 1833. The electrical industry depends, and always has depended, entirely on scientific discovery. Rule of thumb has never played more than a very

alternatively one could proceed from some *a priori* idea of how a society is likely to change, making use of such partial historical parallels as can be found. The former seems to me the more promising and this book is an attempt, a very imperfect attempt, to advance on these lines.

I shall assume that either the world is relatively peaceful, or at least that such wars as arise do not do vastly more damage than those of the immediate past. Some may think that this is an unjustifiably optimistic view, having in mind the almost limitless powers of destruction of 'atomic' weapons. I can only say in reply, first, that if you assume the opposite then the question of the future of the present civilization, which we set out to consider, is answered, and second, that the actual destruction in wars bears little relation to the destructiveness of the weapons used. It has much more to do with the intensity with which men hold the beliefs for which they are fighting and the degree of misery that those on the weaker side will endure before they give in. Indeed the weaker side is often simply the one that will endure the least. It may matter little whether cities, and their populations, are destroyed at long range by 'atomic' guided missiles, or at short range by men with spears and torches. The chief danger that I see from 'atomic' weapons is that one or both sides, in their eagerness to get a knock-out blow in first, may do more damage than would have been necessary to cause surrender if it had occurred more gradually, giving time for its significance to sink into men's minds, and produce its full effect in inclining them to peace.

will certainly miss a great deal. To guess how people will change their lives in response to this progress is much more risky, but it is hard to resist some attempt to do so, however briefly.

Scientific principles are frequently 'principles of impotence'. They say that certain things *cannot* be done, and though they do not say that everything else *can* (for that would mean that there are no more such principles to discover), it is surprising how quickly the most difficult and intricate developments get made when no principle interferes. The rapid development that has followed de Forest's addition in 1907 of the third member to Fleming's thermionic valve, which in turn depended on the discovery of the electron, is a case in point. In radio and in radar, in television and in the huge 'digital computers', which are the nearest approach anyone has made to a brain, the same basic ideas are applied and even the same components used, just as the elephant, the frog and the pigeon work with much the same nerve and muscle cells, moving the same kind of bony structure.

It is worth trying to explain, as far as one can do so in quite non-technical language, what these principles of impotence are. The order is arbitrary, but I shall take as number one the principle whose importance was first stressed by Einstein, that no material object and no signal can go faster than the velocity of light. Electrons have been made to go within one part in 100,000 of that velocity, and in cosmic rays the gap is sometimes even less, but these particles show special properties, which confirm the impossibility of

minor part in developing it; and all the great, and most of the minor, advances have been made as the result of definite scientific discoveries. By the end of the nineteenth century this was true of other branches of engineering as well. Parsons' steam turbine was a development scientifically based on thermodynamics. The use of the microscope made metallurgy scientific, a most important change. For the archæologists are right to speak of the ages of stone, of bronze and of iron. The possibilities of a culture are limited by the material at its disposal, though not every culture reaches the limit thus set. For example, the limit for iron, pure or with some adventitious carbon, was not reached till the nineteenth century though the first iron was worked close on four thousand years earlier and culture had followed culture. Chemistry became scientific in the later seventeenth century, but even earlier the mystical theories of the alchemists allowed some practical progress and the idea of a chemical experiment became part of the mental apparatus of common men. Biology, outside of medicine, had to wait till Bateson rediscovered Mendel's work before it became of much technical importance as a science, as opposed to the mere introduction of plants and animals from one country to another.

It is because major discoveries are likely to be based on scientific principles rather than on mechanical ingenuity, and because these principles have limitations, that it is reasonable to hope to be able to predict in a general way the trend which these discoveries will have. For this reason it may not be too rash to regard certain kinds of technical progress as foreseeable, though one

else' has to be another part of the same body, and there the pole must remain; but the electric charges, though created close together, can be separated at will.

Numbers five and six are also related in the sense that both belong to the quantum theory. Number five is the most difficult to express, but speaking very roughly it states the impossibility of making an accurate survey of a particle, or set of particles, of atomic or sub-atomic sizes. An attempt to measure accurately where the particle is, produces an unforeseeable disturbance in its velocity, so that whatever this may have been before it is now uncertain. Conversely the velocity can only be measured accurately when the position is uncertain This is known as Heisenberg's 'uncertainty principle'. It seems to be absolutely fundamental in the world and has consequences for the philosophy of physics more far-reaching than one might at first expect. It has obliged physicists to reconsider their ideas of cause and effect and of determinism, with consequences which are still the subject of discussion. Nature seems to be woolly at the edges, not clear-cut like an accurate machine, as the nineteenth century imagined it. The sixth, Pauli's exclusion principle, can be regarded as a kind of special force operating in certain cases between two or more particles of the same kind to keep them out of one another's way.

The seventh and last principle differs from all the others in that it only applies where large numbers of objects are concerned and in this sense is less absolute; since however any ordinary piece of matter—even a single biological cell—contains countless millions of

making the last step—which in this case is the one that counts.

If a physicist had been asked to make this list fifty years ago the two first principles would probably have been the conservation of mass (mass cannot be created or destroyed), and the conservation of energy. Now the two have been combined and one can say that mass is conserved if, and only if, energy is conserved also in the region of space considered; and conversely that energy is conserved if mass is conserved, but that mass may be changed into energy and vice versa at a constant rate of exchange. The explosion of an 'atomic' bomb is in fact the conversion of a very small amount of mass into a very large amount of energy. Less than a gramme (1/28 oz.) would give the Hiroshima explosion. This combined principle will be our number two. Closely allied to number two, and indeed derivable from it by the principle of relativity, is the conservation of momentum, which is identical with what schoolboys learn as Newton's Third Law of Motion: Action and Reaction are equal and opposite The backward momentum (speed times mass) of a gun just after it is fired is equal to the forward momentum of the shot. When a ship with the engines idling is slowed down by the resistance of the water, the loss in momentum of the ship is compensated by the momentum of a forward surge of water.

Numbers three and four are similar and say that one cannot make an electric charge, or a magnetic pole, without making an equal one of opposite sign somewhere else. In the case of magnetism this 'somewhere

else' has to be another part of the same body, and there the pole must remain; but the electric charges, though created close together, can be separated at will.

Numbers five and six are also related in the sense that both belong to the quantum theory. Number five is the most difficult to express, but speaking very roughly it states the impossibility of making an accurate survey of a particle, or set of particles, of atomic or sub-atomic sizes. An attempt to measure accurately where the particle is, produces an unforeseeable disturbance in its velocity, so that whatever this may have been before it is now uncertain. Conversely the velocity can only be measured accurately when the position is uncertain This is known as Heisenberg's 'uncertainty principle'. It seems to be absolutely fundamental in the world and has consequences for the philosophy of physics more far-reaching than one might at first expect. It has obliged physicists to reconsider their ideas of cause and effect and of determinism, with consequences which are still the subject of discussion. Nature seems to be woolly at the edges, not clear-cut like an accurate machine, as the nineteenth century imagined it. The sixth, Pauli's exclusion principle, can be regarded as a kind of special force operating in certain cases between two or more particles of the same kind to keep them out of one another's way.

The seventh and last principle differs from all the others in that it only applies where large numbers of objects are concerned and in this sense is less absolute; since however any ordinary piece of matter—even a single biological cell—contains countless millions of

atoms and molecules, it is applicable in the vast majority of practical cases. Its technical names are 'second law of thermodynamics' or alternatively 'law of entropy'. In essence it is the principle of chaos (if that is not a contradiction in terms): it asserts that order always tends to disappear till complete chaos is reached—a chaos which paradoxically enough is amenable to (nearly) precise mathematical treatment, as was shown by Maxwell in the case of a gas regarded as a collection of a vast number of particles moving at random. Order can only be created or increased in a system by action from outside, but order of one kind, such as absence of random motion, can replace order of another kind, such as that which consists in a number of objects all pointing in the same direction. A process of this last kind is in fact used in laboratories for reaching the greatest obtainable degree of cold.

Now it would be rash to suppose that these seven principles will remain for all time. As I have just said, one has been formed from two older ones which seemed in their day well established. But it would be still more rash to suppose that they can be modified in any particular way.

There may well be other valid principles—none so far refers to biology. Is it exempt except in so far as it must conform to the principles of physics and chemistry? It hardly seems likely. Animals and plants have to be able to reproduce and grow as individuals from a relatively very small seed or egg, which yet contains the pattern of the whole. There must be limitations introduced here. Not every arrangement of bones and nerves and

muscles, even though it might make a viable animal, could, one would suppose, grow from an egg—still less be developed by evolution. Perhaps this is why nature never has produced a workable wheel or even a 'caterpillar' track. Everything is reciprocating, though there must surely be situations, in animal life as in the technical world, where continuous rotation would be better.

There is one feature of the world we live in which is so general and so universal that it seems to have escaped proper notice. For want of a better name I will call it the 'principle of mass production'. It is the tendency which nature shows to repeat almost indefinitely each entity it makes. This is most obvious perhaps among the smallest of objects. There are about enough atoms in the ink that makes one letter of this sentence to provide not only one for every inhabitant of the earth, but one for every creature if each star of our galaxy had a planet as populous as the earth. But there are in the universe less than one hundred kinds of atoms, and these hundred themselves are made of a very small number, two or three, of common constituents, electrons, protons and neutrons (if the latter are to be given independent status). At this level the individuals of the multitude are identical; that they are strictly indistinguishable is a principle of the quantum theory which might rank with our other principles of impotence. Larger objects are no longer strictly identical, but closely similar. Examples come both from animate and from inanimate nature. Drops of rain, grains of sand, particles of smoke, bacteria, the cells

of any piece of apparently homogeneous organic tissue, in every case though there may be a large variety of distinguishable kinds each kind exists in numbers which even the cold mathematician must describe as considerable and which to the ordinary person are incalculably immense.

Especially in the living world is this noticeable. A beech-tree is one of a species which contains a vast number of individuals, each indeed different, but clearly distinguished from other creatures made of much the same materials—whales or orchids for example. Each tree has in season a large, though not perhaps quite so large, number of leaves; each leaf is made of relatively few kinds of cell, each kind present in very large numbers. Each cell is made of molecules of various kinds, some of which—though perhaps not all—are extremely numerous. Certainly the whole is made of enormous numbers of a few kinds of atoms. It is the same if we look up to the sky, 'as the stars of heaven and the sand of the sea shore for multitude'. A galaxy has thousands of millions of stars, and there are certainly thousands of millions of galaxies. Not every star is the same, as the psalmist pointed out. They can be classified, though the classification is perhaps a bit vaguer than that of plants or animals. Yet though they differ, a star is a star. Few are more than ten times as massive as the mean, few less than one-tenth of that mean, though their luminosity may differ much more.

To my mind this multitudinousness is the outstanding fact in the universe as we know it. There is nothing in logic to demand it. Though apparent to the careful

observer using only his unaided sense, the advance of scientific instruments and knowledge makes it much more striking. To a certain extent indeed it is the result of language; we give names to recognizable classes and, since we have only a limited number of names, the classification is sometimes arbitrary, giving the impression of sharply-defined species where perhaps none exists. But it is more true to say that natural classification has moulded our language. Because there exist recognizable groups, each containing many individuals, man has invented the 'universals' which have played such a part in metaphysical argument.

This, one may be sure, is one of the fundamentals of the world which further discovery will not alter. Atomicity in its widest sense, mass production by nature, is the deepest of scientific truths.

There are a few still unexplained numerical relations between apparently fundamental physical quantities. The simplest positively-charged particle, the proton, has a mass about 1837 times that of the corresponding negative particle, the electron, though the charges are equal and opposite. There is a certain number 137 which comes into atomic structure and which Eddington thought he had explained, though the few who can follow his argument are unconvinced. From these facts and principles, and from the laws of electricity, follow the laws which govern chemistry and the massing together of atoms to form solids and liquids.

Finally, in this list of unalterable facts and principles, come the absolute sizes of the fundamental atomic units —quantities such as the mass of an electron in grammes

or pounds, the velocity of light in miles an hour or kilometres a second. What these really assert is not the mass of the electron, or the speed of light, but our own mass and the sort of speeds we can produce—the three miles an hour of walking or the two-thirds of a kilometre per second of a rifle bullet—in terms of natural units. They express where our bodies or our common implements stand in the natural scale of things, the scale of the atoms and, at the other end, of the stars. For man is poised between. Very large compared with any atom, he is yet so small that he is quite unaware of the gravitational attraction his body exerts on all around it, unless the other object is as large as the earth. Then he calls it his weight, and sometimes fusses over it. Usually he modestly regards it as the attraction of the earth on him, though as Newton pointed out, it is just as much his attraction of the earth. If a man were as large as the moon or even quite a bit less he would have to be spherical or nearly so, wherever he lived. No material could make, for example, a neck capable of supporting such a head without being crushed, not merely because of the attraction of the earth (if he happened still to live on it) but because of the mutual attraction of a body and head of that size.

Another 'scale-effect' distinguishes man from insects. A water-beetle can run about on the surface of a pond without getting wet, a man cannot, still less a liner. This is because surface tension is very important for an insect, unimportant for a man and wholly insignificant for a liner. A greased needle can lie on the surface of water, making a dent in the surface and being held up by

forces of attraction between the water molecules, which produce the appearance that the water is covered by an elastic skin. This skin always exerts a certain force; if that force suitably directed will not support the needle the skin breaks and the needle sinks. Now double the length of the needle and also its diameter (which may be thought of as both its breadth and its height). It will weigh eight times as much. But it only has twice the length for the skin on the water to pull upon. It is clearly much more likely to sink. By the time the 'needle' has reached the size of a man, though he be greased as for a Channel swim, yet surface tension will be a negligible help. It is true that surface tension varies somewhat from liquid to liquid, but only within relatively narrow limits depending on the nature of the forces between atoms, which in turn depend on the laws of quantum mechanics, on our fifth and sixth principles, and on the sizes of the atomic constants. We shall never see passenger-carrying water-beetles!

On the other hand, we are better off aerodynamically than the insects, which are rather small for efficient flight and have to move their wings at a rate that must surely be inconveniently fast. Here, however, there is a limit to one's useful size, depending on the speed; and provided we want to go as fast as in fact we do, we should gain very little from being bigger. Indeed at supersonic speeds it would be a disadvantage, for cooling would be more difficult.

Size also comes into the problem in a rather different way, as a general limitation on what man can do. After all, we are very small compared with the earth and

or pounds, the velocity of light in miles an hour or kilometres a second. What these really assert is not the mass of the electron, or the speed of light, but our own mass and the sort of speeds we can produce—the three miles an hour of walking or the two-thirds of a kilometre per second of a rifle bullet—in terms of natural units. They express where our bodies or our common implements stand in the natural scale of things, the scale of the atoms and, at the other end, of the stars. For man is poised between. Very large compared with any atom, he is yet so small that he is quite unaware of the gravitational attraction his body exerts on all around it, unless the other object is as large as the earth. Then he calls it his weight, and sometimes fusses over it. Usually he modestly regards it as the attraction of the earth on him, though as Newton pointed out, it is just as much his attraction of the earth. If a man were as large as the moon or even quite a bit less he would have to be spherical or nearly so, wherever he lived. No material could make, for example, a neck capable of supporting such a head without being crushed, not merely because of the attraction of the earth (if he happened still to live on it) but because of the mutual attraction of a body and head of that size.

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where the gun has recoiled and damaged the man who pulled the trigger. A very high degree of understanding is needed by those who would interfere with nature in this way. Yet it has been done successfully again and again. Few of the plants we cultivate or the animals we breed are descended from ancestors once wild in these islands.

In technological advance there are three major components, knowledge, energy, materials. The extent to which civilization can extend its control over nature depends on these three. Knowledge, of course, is the most important: without it the others are useless; but the other two might well be the practical limitations. When I was a boy popular science writings were full of dread for the day when coal and oil would be exhausted—which somehow seemed nearer then than it does now. Actually there is ample energy from the sun for all reasonable requirements, though it might be very cumbrous to use. However, the discovery of 'atomic energy' (more properly called nuclear energy), even limited as at present to uranium and thorium, puts this fear away to a very remote future. If great energies are needed, the difficulty will be to make the machines rather than to supply the power.

While energy is all one, materials are various; some may be in short supply while others are plentiful. Improvements are possible in the quality, as well as in the quantity, of the materials which make machines and consumer goods. While we may have difficulty in maintaining the supply of some essential materials, we may also hope for new materials, which will make

our available force seems despicably weak. The energy released by one of the early 'atomic' bombs would hardly suffice to provide a summer shower over a city the size of Washington. It is improbable that the greatest limit to which anyone could push the hydrogen bomb would provide the energy of the famous Krakatoa explosion, which destroyed a small island in the East Indies and gave the Victorians some months of glorious sunsets while the fine dust it threw up travelled in the upper air round the world. Faced directly by the power of nature even on a smallish planet men can only bow their heads. But the power of nature does not always have to be faced directly. There is a large class of what are called 'trigger actions' where a small cause produces a disproportionate effect. A handful of silver iodide may produce rain over quite a big area, as Langmuir has shown. The rain is wanting to fall. The energy is there, provided by nature, but the chain which can actuate the machine is not complete till man provides the missing link Physicists use the term 'metastable' for a state in which energy can be retained for a relatively long time in the absence of some action or substance which facilitates its release. Following a chemical usage the action or substance may be called a catalyst.

One very important kind of catalyst is a living organism. Because under favourable circumstances plants and animals can spread rapidly when given a start, man can produce changes out of all proportion to the effort he has used. But he must be careful. The rabbit in Australia is only one example of many cases

where the gun has recoiled and damaged the man who pulled the trigger. A very high degree of understanding is needed by those who would interfere with nature in this way. Yet it has been done successfully again and again. Few of the plants we cultivate or the animals we breed are descended from ancestors once wild in these islands.

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construction easy and perhaps make certain things possible that cannot now be done.

The advances one may expect in technology in the reasonably foreseeable future will come from a variety of causes, and usually more than one cause will be operative in each case, but let us try listing the main ones.

Here are some, including those we have just mentioned:

(*a*) More power possible because of the increasing use of 'atomic' energy.

(*b*) Better materials.

(*c*) A great improvement in biological knowledge, which is only beginning to catch up on the physical sciences.

(*d*) Increased powers of handling very complex problems, first by numerical, then perhaps by more general methods, which may be expected as the new electronic digital computers are more fully developed.

(*e*) Fresh needs will lead to new techniques which in turn will be applied in unexpected directions, as were many of those made for the war.

(*f*) The ingenuity of inventors, which is often so badly paid, will provide a stream of new devices. Mostly these will be of minor importance, but collectively they will be significant.

(*g*) There may be some quite new and unsuspected physical discovery which will have important applications, but here one is reduced to plain guessing. To make such a discovery is a major achievement, to predict its use beforehand impossible.

CHAPTER II

ENERGY AND POWER

If one compares the present with the last great age of civilization in Western Europe, the Roman Empire, the most obvious, perhaps even the most important, difference is that many things which used to be done by the muscles of men and of animals are now done by power derived from the burning of coal or oil, and that many other things are done by that power which could never have been done by muscles at all. Up to the first century the only use of inanimate power was to drive sailing-ships. About that time water-mills began to come in, apparently from Asia,[1] to release women from the toil of grinding corn, which had been their heavy task since the neolithic age brought in agriculture. By the Middle Ages water-mills were common and windmills beginning, but it was not till the eighteenth century that heat-energy was effectively turned into mechanical power Since that time the consumption of power by civilized nations has steadily and rapidly increased, and the power used per head is a good test of the level of civilization.

By our second principle, work is a form of energy and interconvertible with other forms such as heat, so that power, which is defined as the rate of doing work, implies a rate of transformation of energy—not a loss of energy, for energy is conserved and constant. The only

[1] An account of one is given by Vitruvius, 26 B C.

exception, that energy may be locked up in the form of mass from which it might be released by nuclear action, does not for the moment concern us. Mechanical power is the most obvious and striking of the forms of power, whether it come from steam-engine, internal-combustion engine or electric motor. If one speaks of the demand for power it is of mechanical power that most people think, sometimes too exclusively. Energy is very like money; one can hoard it, but it is only useful when it is being spent, that is when the energy is being transformed from one kind to another. It is the process that is desirable more often than the final state. Consider for example the train that takes a man from home to office every day. To drive it, coal is burnt and its chemical energy turned to heat. In the turbines of the power station this heat, carried by high-pressure steam, is turned into the mechanical power of a rotating shaft. The dynamo at the other end of the shaft turns this into electrical power, which goes back into mechanical power in the motor of the train. This mechanical power does work in accelerating the train when it starts from the station where our friend has got in, and gives it energy of motion, between stations it does work against the air and frictional resistances. The energy of motion acquired in the acceleration is mostly turned into heat in the brakes when the train stops, but if the time-table permits a gradual stop much can be used on the air and frictional resistances as the train slows down to rest. Ultimately it all gets into heat in the air, the rails, and the train. As a mere accident of this apparently rather purposeless transformation of

energy from heat to heat through a complicated cycle, the man in fact moves from his home to his city station. Unless the latter happens to be higher than the former no net work is done on him and he receives no net energy. Even if he has climbed a bit, he loses that height and energy on the trip home. As this will be downhill it requires slightly less electric energy and so, ultimately, less burning of coal than the uphill journey.

Considerations like these make it almost meaningless to speak of overall efficiencies in the use of power. What is achieved is different in kind from what is spent, or, more properly speaking, transformed. Most uses of power aim not at producing a store of energy, but at a rearrangement of matter. The distinction can perhaps be better seen by considering two exceptional cases where this statement is *not* true. Some at least of the food we eat produces muscular power from its chemical energy. Since we accept our bodies and do not desire to change them fundamentally, the ability to move and work is an end in itself. We want a body stored with chemicals that give us the power to use our muscles. There is a minimum requirement of energy for this purpose if we are to be happy and effective; we must capture the sun's energy by means of plants and turn it into food, perhaps through the medium of the bodies of animals This food is edible energy which the war has accustomed us to measure in calories, a unit of heat used also in measuring the energy latent in coal. The other important case is the smelting of metals. Most metals exist in a state of chemical combination in their ores, often as oxides or sulphides They are, so to speak,

burnt and have to be 'unburnt' at a definite cost in energy before they are available as metals. For every ton of steel there is an absolute minimum price in energy. Returning to the analogy with money, it is a little like turning a bank balance into gold and wearing the coins as a necklace. In these cases the second principle applies quite simply and one can speak of a true efficiency. How much of the energy in the coal burnt in steelworks is used in separating the iron atoms from the ore? *Actually not very much, about 18 per cent;* it is fair to call the rest waste.

In most other things we are concerned more with principle seven than with principle two; in technical terms with the second law of thermodynamics rather than the first. Take for example the heating or the cooling of a house. The object is to keep the things in a certain region of space at a different temperature from those outside. There is no necessary gain or loss of energy by the things in the house. The people, it is true, generate heat which has to be removed if their temperature is to stay constant. We are in fact a source of heat-energy—if you forget that we have to be fed. But a state in which one region is different in temperature from its surroundings is an improbable state. Something definite must be done to create this improbability, to pump heat from what becomes a colder to what becomes a hotter body. This requires energy in some form. The simplest way, if the house is to be hot, is to light a fire in it and allow the chemical energy of coal mixed with oxygen from the air to turn into heat-energy by the chemical process of combustion.

The house can also be warmed by a 'heat-pump', a refrigerator worked backwards in which mechanical energy (usually supplied by an electric motor) takes heat-energy from outside, raises its temperature and delivers it to the warm room. Actually this is an efficient process and much less energy is required than would be needed from burning coal; but against this the electric energy is itself made by a relatively inefficient process from coal in the power station, so there may not be much overall gain to set against the cost of the machinery.

Once the difference in temperature is produced, there need be no effort to maintain it if it were not that heat leaks back through the walls. The leak depends on how well the walls insulate the heat; with very thick walls the loss might be made very small. Of course in practice there are limits; air has to be let in for ventilation and will need to be heated, doors must open to let people in and out and then cold air will enter, and so on. But it is misleading, unless one is very careful, to speak of the 'efficiency' of a heating appliance. One can save fuel as well by fitting double windows as by improving the stove. Combustion heating, gas or coal, which requires an inflow of air, necessarily requires more heat to be released to get the same temperature than does an electric radiator, though of course the flow of air may be desirable for health reasons.

As designers of aeroplanes know well, it is artificial, though often convenient, to assign an 'efficiency' to the propeller. The energy given to the air by the moving blades, and so wasted, cannot be sharply distinguished

from that transferred to it by the wings and by the drag of the fuselage. In a sense *all* the energy of the engines is wasted in steady level flight since the aeroplane is in the same state after as before; from the point of view of energy, what is produced by all the power is only a heating of the atmosphere; but the desired effect has been obtained, people and things have been transferred from one place to another.

Many processes of ordinary life consist in, or at least involve, putting things in order, that is into a state less probable than the random one. This, by principle seven, involves a compensating increase of probability somewhere else. One way of doing this is to let mechanical power degrade into heat, and thermodynamics allows one to calculate how much is needed as a minimum. Usually this minimum is far less than is actually used. A spinning-mill, for example, is essentially occupied in arranging the random fibres of a wad of cotton into the ordered structure of thread, but the entropy-change, though not easy to calculate, requires very little mechanical power to be degraded at the temperature of the mill. If a man sorts a random pack of cards so that they are in an assigned order he creates an improbability of 1 in $52 \times 51 \times 50 \times \ldots \times 3 \times 2$. This is a very large number indeed, but the corresponding loss of entropy, which must be balanced by changes in his brain, would only require the expenditure of $6{\cdot}4 \times 10^{-12}$ ergs, about the work required to break a single molecule in half, and less than the energy produced by burning one molecule of paraffin!

These considerations make one chary of hasty state-

ments of future needs for power. So far, during the steam-engine age, raw energy in the form of coal has been relatively cheap; the capital cost of the machinery to apply it has been economically more important. A highly civilized age with a limited power supply might come to regard some of our processes as like burning the house down to roast the pig. Less use of power might be compatible with a higher standard of living. Personally I do not believe that the difficulty will arise. It is extremely difficult to assess how long the 'fossil' fuels will last. Geology is not an exact science. Coal and oil are at present producing very roughly equal amounts of power in the world, but the supplies of coal in the earth much exceed those of oil. There may be perhaps five million million tons of coal reasonably accessible against a present world consumption of about 1,300 million tons per annum—theoretically nearly 4,000 years' supply at present rates, though no one imagines it could all be won. For oil a conservative guess is about 10,000 million tons against a consumption of 400 million, only 25 years' supply. Natural gas probably adds about 40 per cent to the calorific value of the oil, with which it is closely associated. There are large amounts of oil in shale, perhaps 20,000 million tons, but it is not easy to recover. Oil can be made from coal but not at present at a price to compete with the natural product. In any case, the known processes involve a considerable difference between the thermal capacity of the oil produced and the coal used. This difference, of course, appears as heat in the plant; heat which it might not be possible to use.

It ought to be said that this relatively optimistic view of coal supplies is not universally accepted. Some competent authorities consider that it would not be possible to recover more than a small fraction of the reserve indicated; but even this fraction gives a supply for some centuries at present rates of consumption and great improvements are possible in a century. If the continuation of civilization depended on winning this coal, I am sure that it would be won—provided, of course, that it is really there.

Other sources of energy exist and should be considered. The direct radiation from the sun, which bears the same relation in the field of energy to the fossil fuels that income bears to savings, is indeed very considerable. The difficulty here is that it is spread over a large area. To collect it by focusing mirrors and heated water, or some similar device, involves a very large outlay of capital in proportion to the power produced. It is rather doubtful if one would do much better than by growing some rapidly maturing plant and burning it. Wood has been the major fuel and the major source of energy of mankind for many thousands of years and it could well furnish an appreciable contribution. Nor is there any reason to suppose that the resources of biology are exhausted and that it would be impossible to increase the yield per acre of combustible material. This now stands at perhaps 300 cubic feet per acre for wood, yielding from existing forests something like the equivalent of 2,000 million tons of coal per annum if all were burnt; but probably not more than half this at the most could be made available. Water-power, which

also comes in the income class, yields at present electricity which it would require 140 million tons of coal per annum to produce. The best estimate, though it is an uncertain one, is that this might be multiplied by about 20 for the whole world. But, as in nearly all industrial processes, one comes up against a law of diminishing returns. The most convenient sources have already been tapped in most countries, and the more one needs the harder it is to get it and the greater the capital cost involved. It is not likely to supply more than a small fraction of the needs of the future. Tidal power has also been considered, but here again the amount available with reasonably compact installations is extremely small The Severn Barrage scheme, probably the most favourable, is only estimated to yield the equivalent of about one million tons of coal per annum. Heat from the interior of the earth, and power from windmills are sources which will no doubt be used locally, but are not likely to give a major contribution to the world's power supply.

Solar radiation may perhaps have its uses for domestic purposes in remote and sparsely inhabited areas where the costs of transportation are high. The radiation on the roof and walls of a house supplies something like the power required to warm or cool the house. The latter application is perhaps the most promising, for the installation is needed to work when the temperature is high, which is roughly when the radiation is falling; the use of radiation for heating purposes involves storage over rather long periods, which though it is perfectly feasible, means more plant and

more capital expense. The use of solar heat for cooking may prove very valuable in India to save the dung now used as fuel, which is needed as manure. Small power units of a few horse-power may also be useful for irrigation purposes.

If population and the requirements of energy per head were constant the energy of the world would seem assured for quite a long time. Water might provide most of the electrical power, some of the domestic heating could come from the sun, and coal, turned into oil when necessary, could supply the power for processes and for internal-combustion engines for a very long time. Unfortunately neither of these assumptions is legitimate. The population of the world has been rapidly increasing for at least the last three hundred years and though it shows some signs of stopping in the West there has recently been a spurt even there, and in the East the application of modern medicine will probably produce for a time a rate of increase even greater than the present. Careful estimates suggest that the population may be expected to rise from its present 2·5 billion to 6 or even 8 billion by 2050. Further, this rise in population will probably be associated with a change in habits from subsistence agriculture to a mode of life more like that of Western Europe, which will give an increased demand for power per head. The consumption of energy in subsistence agriculture is indeed far from being negligible. Large amounts of wood and farm-waste are burnt for cooking and heating In the first decade of the nineteenth century the *per capita* use of energy in the U.S.A., almost all in the form of wood,

was more than half what it was in the 1930's.[1] Unfortunately energy from wood and farm-waste is not easy to increase and is indeed liable to diminish as forests are cut down and the land used for food for the increasing population.

There is a steady tendency for the *per capita* consumption to increase. A good deal of this increase is due to the desire to have energy in its most convenient form, electricity rather than heat for example, while coal may soon be turned extensively into oil, in both cases with a substantial waste. Putnam[2] considers that a rise of 3 per cent per annum in power *per capita* actually used is a reasonable estimate and 5 per cent is possible. After careful allowance for changes in efficiency he comes to the conclusion that the annual power input required by the world in 2050 may be about 30 times what it is now. This, of course, makes nonsense of a civilization based on fossil fuel—especially as sources of power such as wood, farm-waste, etc., cannot be stepped up, so that the demand on the coal is increased by more than this proportion. If the cost of power were to rise steeply, other ways of getting power would become possible economically, and the problem would change. Even the proposed rate for 2050 is less than one-thousandth of the energy reaching the Earth's surface from the sun. A rise in the cost of power would decrease the demand, but it might also tend to retard progress and to take the zest out of technology. This might be, but I think that many economies in the use of power are possible

[1] Ayres and Scarlott, *Energy Sources—the Wealth of the World*, McGraw Hill, 1952, p 285

[2] Putnam, *Energy in the Future*, Van Nostrand, 1953, p 107 fig

and would come into use as soon as the cost of power rose seriously. As I have tried to show in the first part of this chapter, the power needed for a given standard of living is by no means a fixed quantity. It might be drastically reduced by not very difficult technical advances. But I do not believe this will be necessary: nuclear power is already beginning to be used and its possibilities of expansion are enormous.

Nuclear ('atomic') power, as at present used or proposed, arises from the splitting of the nuclei or centre portion of certain of the very heavy atoms when they are entered by neutrons. Since the act of splitting or fission also produces neutrons, which can themselves cause fission in fresh nuclei, a 'chain-reaction' may be possible in which the process goes on faster and faster in geometrical progression, until the material is used up or some change in the condition occurs to stop it: for example, an explosion which scatters the material. An 'atomic' bomb works in this general way and the object of the designer is to explode as much as he can before the rest is driven apart. The original Hiroshima bomb worked with U^{235}, the only naturally occurring substance for which a chain-reaction is possible. This occurs to the extent of about one part in 140 in ordinary uranium, the rest having mostly a mass 238 in the usual units and being known as U^{238}. The presence of the U^{238} prevents ordinary uranium acting as a bomb, but it is just possible to get it to give a chain-reaction by mixing it with the right amount of a suitably chosen 'moderator', usually very pure graphite or heavy water. This mixture, usually in the form of rods of

uranium metal in a larger volume of moderator, is called a 'pile'. The process of fission produces a great deal of energy which in the case of a bomb gives the explosive force and in the pile appears as heat. In principle this heat can be used to boil water or other liquid, and the steam can drive a turbine and dynamo giving electric power. In practice the original piles are unsuited for giving power; they would be damaged by a high temperature and have to be kept cool. The energy is indeed removed in the coolant, but low-temperature heat is very inefficient in giving power, though it can and has been used for space-heating.

The original piles were intended for another purpose, and the heat is an unwanted by-product. During the chain-reaction some of the neutrons attach themselves to U^{238} nuclei and cause these to change into nuclei of another element, unknown in nature, called plutonium. This has properties much like U^{235}, but while it is very difficult to separate U^{235} from U^{238} because most of their properties are identical, plutonium can be separated from U^{233} by chemical means. In effect the pile destroys U^{235} and replaces it by plutonium. The pile is a so-called 'slow' reactor, in which the neutrons are slowed down to a speed of the same order as that of air molecules before they react. The bomb is a 'fast' reactor in which the neutrons react while they still have the much greater speeds with which they are formed. In the ordinary pile rather more U^{235} is used than plutonium is produced, but it is known that it is possible to produce a controllable fast reactor in which on the average for each U^{235} nucleus destroyed, slightly over

one plutonium nucleus is formed. There is thus a net gain which theoretically can be stepped up indefinitely by repeating the process. This is called 'breeding'. It can also probably be done using thorium, the next heaviest element to uranium, in place of the U^{238}. The thorium forms U^{233} which has similar properties to U^{235}.

When it comes to getting useful power, many problems must be solved. The pile must be made to work at a temperature high enough to be an efficient boiler, or rather furnace. Some material must be found which will carry the heat away and not absorb the precious neutrons which are the life-blood of the pile. The whole must be made to work automatically, because it emits great quantities of deadly radiations which must be shielded-off from the workers. In its construction materials which absorb neutrons must be used very sparingly if at all. Most of the ordinary metals are bad in this way. Altogether it is not surprising that it has taken some little time to solve these problems and that nuclear power in more than token quantity is still a news item.

Nevertheless, there is no doubt that it can be done and two piles of the slow reactor type and one of the breeding type are under construction in this country, with promise of more to follow. A British White Paper[1] estimates that it will be possible to produce power at the cost of 0·6*d.* a unit (kilowatt-hour) allowing for the value of the plutonium produced. This is a very reasonable cost, particularly in view of the experimental nature

[1] Programme of Nuclear Power, 1955

of the plant. One may hope that this cost will be appreciably decreased as experience accumulates.

If such plants can be multiplied indefinitely, it will obviously go a long way to solve the problem of supplying energy to a growing civilization, but there are several things which must be considered. In the first place, it has sometimes been suggested that the supplies of accessible uranium are too small to supply an appreciable fraction of the world's power for any considerable time. The heat theoretically obtainable from a pound of uranium (about $3 \cdot 3 \times 10^{10}$ B.Th.U.) as compared with the heat of burning a ton of average coal (about 2.5×10^7) is rather over a thousand times as much. Putnam, p. 214, estimates that about 26 million tons of uranium and thorium are available on the earth at a cost not exceeding \$100 per pound. Assuming that the operation of breeding makes it possible to use the energy from one-third of the whole amount of uranium and thorium extracted from the earth, the heat content is equivalent to that of about 2×10^{13} (20 million million) tons of coal. This is several times greater than the estimated reserves of actual coal.

For an up-to-date generating station about 1 lb. of coal is burnt for every unit generated; with coal at £3 10*s*. a ton power can be produced at a total cost of 0·6*d* per unit, the same as is estimated for nuclear energy. Now though the plant for nuclear energy is rather more expensive to build and maintain than for coal, the cost of nuclear energy would not be a serious burden on a world hungry for power, if the cost of the nuclear fuel per unit became equal to the present cost

of the coal. But a pound of uranium should produce over a thousand times the heat of a ton of coal, and even allowing for consuming only about a third of the uranium, should produce 400 times as much; so one would break even if the uranium cost 400 × £3 10*s.* or £1,400 a pound. The probable cost of the uranium now being used is $20 a pound. There is a big margin for a rise in costs, due to the richer deposits being worked out, before the price of power would rise appreciably. Now the amount of uranium in the earth as a whole is not excessively small. Goldschmidt (German Chemical Society 1937), whose estimate is probably as good as anybody's, takes four parts in a million of uranium and eleven of thorium in average rock. Thus the two together are roughly as common as lead, to which he has assigned sixteen parts in a million. They are in the ordinary sense of the term rarer substances than lead because there are fewer instances in which nature has concentrated them into rich ores, but even the *average* rate of fifteen parts in a million represents ten pennyweights troy per ton, which a gold-miner would regard as a very satisfactory ore. Doubtless uranium is harder to concentrate than gold, and doubtless the cost of extraction from ores such as these will exceed $20, and even $100, to the pound, but methods of extraction improve, and I have little doubt that practically unlimited quantities of uranium and thorium could be available at prices which would not raise the price of power substantially above what it is now.

But this is not all. There is every reason to suppose that in the not very distant future the nuclear reactions

which produce the energy of the hydrogen bomb will be tamed. In this case the power arises principally from deuterium, the so-called heavy isotope of hydrogen. This is present to the extent of one part in seven thousand in ordinary water, and although the extraction is a reasonably expensive process it would not add appreciably to the cost of the power. The nuclear reaction is of a very different kind. It is an example of power from building up the light nuclei rather than from breaking down the heavy one; the end-product is the relatively inert helium nucleus. We may fairly assume then that electric energy can continue to be produced in almost any quantities that we want, at a price not exceeding that at which it is sold today—perhaps when techniques have been improved at a somewhat lower cost.

Now, how will this affect power in general? Nuclear energy has its limitations. Every nuclear reaction leads to the production of large quantities of radiation harmful to life, and a reactor powerful enough to give a worth-while amount of energy will require to be surrounded by many feet of absorbent material. It is therefore wholly unsuited for use, for example, in a motor-car and has serious disadvantages in an aeroplane, at least in one that has to carry a living load.

Again, in many of the uses of coal its chemical properties are involved. Thus large amounts of coal are turned into coke and used in smelting iron, where the chemical energy, or part of it, is made use of directly in producing a chemical change; though much, of course, is used to produce that heat at which alone the

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The difficulties of producing electrical energy directly from nuclear reactions are technical but substantial. At present no one has suggested a feasible way of doing it on a substantial scale in the case of the fission reactions which alone have been achieved to date. The difficulty arises from the great disparity between the ranges of the fission fragments, which will only go through a few millimetres of air at atmospheric pressure, and those of the neutrons which produce them and which will go through as many metres. The fission fragments carry the charges, and so on the face of it it would seem that one could only collect the charge from a thin layer on the surface of the mass in which the neutrons are active. This difficulty may perhaps be overcome by ingenious design, but it may be found easier to use the thermonuclear fusion reactions when these are achieved. Here the particles producing and resulting from the reaction are more similar and this particular difficulty does not arise.

As we come to depend more and more on nuclear reactions, energy will undoubtedly be used increasingly in the form of electricity. This is in accordance with the present trend and will not necessarily produce any very drastic changes; even now, when it is expensive, electricity is preferred to other forms of power because of its convenience. Obviously all railroads would be electrified. The terribly inefficient steam locomotive has already been displaced in many places by the diesel engine, but this will probably go in turn as oil fuel becomes scarce.

The extraordinary convenience of oil as a portable

change occurs with the necessary speed. It is indeed possible to produce steel from electricity, but at a considerably greater expense of energy—the process is less efficient. As electricity, when generated from coal, involves the loss of two-thirds and sometimes three-quarters of the heat-energy in the coal, the double inefficiency makes the process quite uneconomical. If ever our coal was used up and electrical power was abundant and cheap, the circumstances might change. Actually satisfactory coke for use in the present blast-furnaces can only be obtained from special grades of coal, and there is likely to be a shortage of this quite soon—in Great Britain at least. Perhaps it will prove possible to overcome this difficulty and to use other kinds of coal for smelting purposes. Or perhaps the shortage of coking coal may drive us to use electrical methods of smelting earlier than might be supposed, and to find some way of doing it that is reasonably efficient. The efficiency with which heat can be turned into electricity depends mostly on the temperatures that materials will stand. It is a question of thermodynamics and it is perhaps not likely that a very great improvement in efficiency will occur; probably not as great as has been seen in the past forty years. But there seems no reason why the application of the electric power once produced should not be made reasonably efficient.

Since nuclear reactions, whether by fission or by fusion, produce electrically-charged particles, it might be thought that the process of turning their energy into heat and then back again into electricity is extremely cumbrous and wasteful, and so in a sense it is.

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fuel for use in small units, for example in motor-cars, is likely to lead to oil of a kind being made available even after all the natural deposits have been exhausted. In the first instance it will probably be made from coal, as it was by the Germans during the late war. It is perhaps rash to predict whether oil will still be used a few centuries hence when the coal has gone, though I am inclined to think that it will. Oil is a mixture of many complicated compounds of hydrogen and carbon, and there is no obvious reason why, if sufficient power was available, the carbon could not be derived from the practically inexhaustible supply of limestone, and the hydrogen from water. But it is possible that before one reaches that stage some really satisfactory electrical accumulator will have been devised, and the internal-combustion engine become obsolete.

The heating of houses seems one of the uses of power in which considerable economies could be made. If cheap electrical power is available, the heat-pump allows it to be applied very efficiently for this purpose. The heat-pump is really a refrigerator in which instead of creating cold inside the refrigerator by taking the heat away and then discarding the heat, you have the refrigerator out of doors and introduce the heat into the house. In both cases by the use of energy heat is carried from a cold body to a hot one contrary to the trend of nature. Now, if the difference in temperature is not very large this process can be markedly efficient, and four or five times as much heat can be stepped up as corresponds to the energy used. With electricity produced from nuclear energy as the standard power it is

the obvious way of heating houses. Possibly in cities nuclear heat directly produced and circulating in hot-water ducts might have advantages, as if too much heat is sucked out of a limited amount of ground by heat-pumps the temperature there would fall unduly.

For many purposes, of course, the present kind of direct electrical heating has advantages; if heat is only required in a particular room for half an hour a day it is an excellent method. Finally, domestic heating will, I hope, continue to use the oldest method, the wood fire, which first gave man a taste of the possibilities of power. The income from the forests of the earth is by no means negligible and for æsthetic reasons, if for no other, will continue to be used.

Ships can be well adapted for the use of nuclear power. There is enough space to shield the harmful radiation, and the saving in bunker-space is quite important for long voyages. I think we may expect shipping to go nuclear about the time that the natural oil gives out.

It must be emphasized that even the discovery of effective ways of releasing nuclear energy from heavy hydrogen would not necessarily mean very cheap power. The cost of power even now is largely interest on capital, depreciation and running costs. These may or may not be less for nuclear energy than for coal or oil. As technique improves costs will tend to diminish as measured in terms of man-hours, but not necessarily as measured in terms of other products. Any project which requires very large amounts of energy will always be an expensive one, but the cost of energy per

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CHAPTER III

MATERIALS

ARCHÆOLOGISTS have long been in the habit of labelling civilizations by the main material which they used; stone ages, bronze ages and the like. This is not only a convenience but expresses a real truth, for a civilization is limited by the materials at its disposal. In our own case the last fifty years have seen the introduction of a great range of new materials; light alloys based on aluminium and magnesium, plastics, steel containing other metals and not merely carbon, are obvious examples. Indeed it is extraordinary how many of the ninety elements found in nature have now been applied to industrial uses, while a century ago all except about twenty were chemical curiosities. Among the latest to become important are titanium, as a main constituent of light strong alloys; germanium, which has special properties that promise to make it a substitute for radio valves; and zirconium, important for construction of nuclear energy plants because it absorbs neutrons so little.

Is civilization likely to become more and more dependent on this variety of materials; to what extent will substitution be possible; are shortages likely to arise? The advantages of using a wide range of materials are so obvious that very great efforts will certainly be made to keep up a supply. Perhaps no one substance is quite indispensable, but undoubtedly there are many which

unit will not depend as much on the number of units which civilization needs as it would have done if, for example, we had to depend to any considerable extent on water-power. Then there would have been a pretty definite limit to the power obtainable at a reasonable cost. As it is, mankind can safely plan very large-scale projects if they promise a good return on the effort invested. This is particularly important when one considers the possibility of large-scale changes in climate.

generations, hardly for many centuries if demand continues to expand. Then one must either go deeper or use poor ores.

Methods of geophysical prospecting have developed rapidly in recent years; so far they have mostly been used to look for oil, but most of them are also applicable to metallic ores. The methods used include: examination of the minute changes in the weight of a mass due to variations in the density of the rocks that attract it from below; magnetic effects; irregularities in the conduction of electricity through the earth between distant points (which may give an indication of what rocks are below the surface); and also studies of the way in which shock waves from an explosion in the ground are transmitted. In spreading through the earth these waves are reflected at the places where one kind of rock changes into another, and their speed of propagation, which can be measured, depends on the properties of the rocks.

By an extension of these methods it should be possible to locate ores at greater depths than can now usually be done Whether mining can effectively be carried out at depths much greater than those now reached in some gold-mines may be doubted, but even if that is taken as a limit, there must be a great deal still to be found. All the same this is fundamentally only a palliative and such finds will eventually be exhausted. The amount of a rare constituent of the earth which exists in rich ores is negligibly small compared with that which exists in very low concentration. The problem is how to handle enormous masses of material in order to extract very little. The 6 dwt. to the ton

it would be a great deprivation to lack. Speaking first of minerals and their derivatives, the most obvious thing that strikes one is the enormous disparity in the quantity that nature puts at our disposal. A few elements account for the great bulk of the earth's crust, and of the useful metals only iron, aluminium, magnesium and titanium are really common. Even here one may be restricted; practically all the aluminium now produced commercially comes from the not very common mineral bauxite, though aluminium is a substantial constituent of most clays. However, the difficulties here are more economic than technical. Aluminium can be extracted from clay at a price, and if bauxite runs out, there is no doubt that it will. But the other useful metals, even relatively common ones like copper, run in parts per 100,000, while the rarer ones are less than one in a million of the earth's crust. Man would have had a poor time of it metallurgically if the natural processes of geology did not sometimes produce surprisingly great concentrations of these rare elements. But these rich ores are rare, and large regions of the earth are almost entirely devoid of them. There is not much of the solid surface of the earth, except that part covered by ice, which has not been at least superficially examined for minerals. No doubt many valuable deposits have been overlooked (one has only to notice how finds of uranium occur now that it has become highly prized) but there is a limit and probably not a very distant one. With rapidly increasing production of most metals the rich ores near the earth's surface will be exhausted. They will last for decades, perhaps for

generations, hardly for many centuries if demand continues to expand. Then one must either go deeper or use poor ores.

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large enough for magma to flow up it without solidifying will be very expensive, and one would not risk putting it in the wrong place. With luck the magma will be forced to the surface by natural pressure, or perhaps by water forced in behind it and turned by the heat into high-pressure steam, otherwise some kind of pump will be needed. The difficulties are great, but the need will be great also, for civilization without the rarer metals will be hard pressed.

Nature has provided us in the ocean with a fluid ore very easily handled, and there is no difficulty in getting rid of the tailings. The concentrations are indeed low, and bear no simple relation to those in the surface rocks. For example the rare boron and lithium are present to 4 8 and 0 12 parts in a million, while iron occurs only to the extent of two parts in a thousand million. Iodine, which is a very rare element in surface rocks, occurs to five parts in a hundred million, and though this seems little, certain seaweeds can concentrate it so effectively that for many years they were the main commercial source of the element. Five parts in a hundred million is about 86 lbs in a cube of sea a hundred yards square and fifty fathoms deep. What is more remarkable is that certain sea-animals use copper as an essential constituent of their blood, and one even uses vanadium. Now copper is only present to the extent of two parts in ten thousand million, 10^{10}, and vanadium slightly more These examples show that biological methods of concentration can be very effective and suggest that they may be worth developing. It may be possible to breed plants or other organisms which will concentrate

of a fairly good Rand gold-mine is about one part in a hundred thousand by weight, and the costs to extract it are comparable with the value of the gold. Very substantial improvement is needed before it would be feasible to mine copper or even tungsten at so low a concentration. There are probably very large deposits in which an element is present at, say, ten times the average concentration, and it may not be beyond the powers of traditional methods to produce the needed amounts of certain elements for a long time. However, there are two other possibilities worth examining.

One of the reasons why conventional mining gets difficult at great depths is the increasing heat. Temperature increases by something of the order of 10° F. per thousand feet and the problem of keeping cool becomes serious at a depth of a mile. It might be possible to mine to great depths by the technique of the driller for oil. Instead of human miners going underground it is conceivable that one could locate veins of molten magma by one of the methods described above and bring it to the surface as a liquid. While it is not now believed that much of the crust of the earth is molten, ores have probably been deposited from liquids, either molten or solutions at high temperature and pressure. Presumably such veins of liquid still exist inside the earth.

One problem will be location. The properties of a magma containing metallic ores are sufficiently different from those of ordinary rock for detection to be possible; probably it will be necessary to lower the instruments down narrow bore-holes somewhere near the suspected vein so as to locate it accurately. A shaft

rarer elements will be driven hard to keep up the supply. Unfortunately it is not a universal answer; some important elements, for example tin and tungsten, do not apparently exist in the sea in detectable amounts.

It is of course true that in a sense rare elements are not used up. They still exist somewhere on the earth. What is used up is the effort spent in concentrating and purifying them, since they are thrown away and disappear into a general mixture. Theoretically elements may be made by nuclear change, as plutonium is made in a pile to use in an atomic bomb, though not all elements can be made as simply as is plutonium nor would there usually be a plentiful raw material. However, the real drawback is the scale. Perhaps by now a few tons of plutonium may have been made in the world, but at what cost! A process of this kind is out of the question where the demands are for thousands, even millions, of tons a year.

Improvements in Strength

Perhaps the most interesting possibility about materials is that of greatly increasing their strength. Solids are held together by the forces between the atoms that compose them. These forces are capable of rough calculation. When calculations are compared with facts it is found that all materials are much weaker than they ought to be—by a factor of perhaps a hundred. It does not seem likely that the forces have been badly miscalculated; rather it appears that materials break because of faults not essential to their structure. When a piece of hardened wire is stretched its resistance to

groups of elements to a stage at which extraction becomes easy. An alternative, but perhaps less promising, method would be to develop ion-exchange resins of the kind used in producing fresh from salt water and supplied to ships' lifeboats in the last war, but the amount required would be enormous.

Since, in general, work has to be done to produce order (principle seven), there is a minimum requirement of work to concentrate a dispersed substance. Though this work would theoretically be infinite at infinite dilution it is not excessive even when the dilution is fairly high. For example, to concentrate a ton of copper in solution from a dilution of 2 in 10^{10}, where it would occupy 5×10^{9} cubic metres, to a volume of 1 cubic metre would only require 240 kilowatt-hours at 15° C. But this of course is only a theoretical minimum; the actual effort involved depends enormously on how skilfully the separation can be done. Probably some kind of biological or chemical process would have to be used. The sea-water might be induced by the action of the tides to flow past surfaces, whether plastic or living growths, which would have the power of extracting the substances required and perhaps even sorting them out as in the new analytical method of chromatography. This is undoubtedly a long way ahead. The problems, both mechanical in arranging the flow of sufficient quantities of sea-water (which must be perpetually mixed with the ocean or it will be too depleted in the substance to work) and chemical or biological in the actual extraction, are extremely formidable, but a civilization perpetually using up the

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extension at first is not greatly different from what is expected, but instead of being able to stretch with steadily increasing resistance till it has elongated by about 10 per cent, it begins to flow at perhaps 0·5 per cent extension and though it may extend much further before actually breaking, does so without marked increase in resistance.

There are many complications to be considered. For example, Griffith showed many years ago that thin glass fibres can be made much stronger, in proportion to their cross-section, than ordinary glass tube or rod. This is because the thin fibres can be made quite free from the cracks on the surface which are always present in larger specimens. When a force is applied to the specimen the stress concentrates at the crack-end and opens it up almost like a zip-fastener, so that the specimen breaks under a far smaller force than would have been needed if it had been distributed fairly over the cross-section. This effect is more important with a very hard brittle substance like glass than it would be in a tough metal like wrought iron. Here the concentrated stress would make the metal flow before it broke, and by flowing it would alter the shape of the crack and reduce the stress.

The position with metals is a curious one. In practice they usually fail by 'shear', that is by slipping of one layer over another. Ordinary metals are composed of a mass of tiny crystals arranged at random; thus the slipping of one layer of metal over another involves the cutting of these interlocking crystals in directions differently disposed to their faces. The position would

clearly be simpler if we had a single crystal large enough to test. It is now possible in fact to make such crystals. They show the remarkable property of being extremely soft; they shear and deform with very small forces. This is very odd, because it is these single crystals, one would have supposed, to which should apply the calculations which predict great strength. A great deal of study has been spent on this and allied questions in recent years. It is believed that faults of a special kind in the crystals called 'dislocations', play an important part. A dislocation is a region of misfit in the crystal, in the form of a long thin cylinder; the axis of the cylinder is the 'line' of the dislocation, and associated with this line is a plane over which that part of the crystal lying on one side of the line can be considered to have slipped. In certain circumstances the line can move at right angles to its length and by so doing spread the region over which slip has occurred. Dislocations can be of two principal kinds, called 'edge' and 'screw' according to the nature of the misfit they contain

It is supposed that the softness of single crystals of metals is due to the presence of a number of these dislocations which move with very little resistance through the metal, allowing easy slip. Single crystals of metal as well as polycrystalline metal specimens are readily hardened by distortion. Many theories and many experiments have been made on this 'work-hardening'; while there is not agreement on details it is generally believed that the working of the metal produces a number of dislocations in different directions which

lock against each other and so can offer substantial resistance to slip. This accounts for the moderate strength of normal metals, but since the dislocations are still there they never reach anything near the ideal of a perfect crystal.

That it is possible for a metallic crystal to resist relatively great changes of shape is shown by recent experiments on crystals of tin in the form of very fine wires which can be made to grow from the surface of the metal as 'whiskers'. Although large single crystals of tin slip at strains (change of shape) of 1 in 10,000, these whiskers require strains of 2 or 3 per cent before they distort permanently. It seems that the possibility exists for metals far stronger, perhaps a hundred times stronger than those we have at present. The difficulties in producing them are obviously very great and no one is prepared yet even to suggest a way of achieving it. But with rapidly increasing knowledge ways may appear. It seems very unlikely that the elements of weakness are so much in the nature of things that it is impossible either to eradicate them or so to sterilize them as to prevent them causing easy rupture.

There is a rather similar position with organic fibres, both natural and artificial. Both natural and artificial fibres are made of very long molecules containing thousands of atoms each in a chain. The chains tend to be orientated, but usually imperfectly, along the length of the fibre. It is possible to calculate the force required actually to rupture a chain, and if breaking the fibre meant that all the chains broke at once over the cross-section the strength would be about 20 times

as great as is the case even for the strongest natural fibres such as hemp.

Two alternative explanations present themselves. The long chains in the fibre may not be equally stressed, so that some break first and transfer an unfair load to the remainder, breaking each in turn. Against this one may argue that the long-chain molecules would give very substantial elongations (10 per cent or more) before breaking and one would expect them to yield enough to spread the stress adequately. The other explanation is that the fibres yield mostly by the molecules slipping over one another, each molecule remaining intact Calculations on these lines give the right order of magnitude for the breaking strength. The forces which hold the molecule together sideways and prevent one slipping over the other are the so-called 'Van der Waals forces' which are much weaker than the true chemical forces (co-valent bonds) which hold together the atoms that make each chain.

Theoretically there would seem to be room for improvement in several ways. The longer the individual molecules, the greater the area of contact between one and its neighbour—the greater, that is, the area over which the Van der Waals forces can act to glue the two molecules together But though experiments show an increase in strength with length of molecule, the increase is not indefinite but levels off at a certain length. Perhaps avoidable irregularities of arrangement or composition cause one part of a molecule to stretch and slip over its neighbour before all the forces take the strain. Another possibility would be to try to bond the long

lock against each other and so can offer substantial resistance to slip. This accounts for the moderate strength of normal metals, but since the dislocations are still there they never reach anything near the ideal of a perfect crystal.

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tolerated and here the stronger material scores. For example, if a building has to be designed to stand up to wind stress, it may be admissible for it to bend quite considerably to an occasional hurricane, provided it recovers when the stress is past. One may expect that improved materials will allow many kinds of design to be made much lighter and more flexible. An aeroplane wing may become much more like that of a bird, yielding markedly to gusts. The cables of a suspension bridge may be permanently extended by the weight of the bridge to be 10 or 20 per cent longer than their unstretched length, and will be correspondingly lighter —more than proportionally indeed, for in a long bridge a substantial part of their load is their own weight, and this is reduced by making them thinner. Deliberately arranged springs will in many cases be no longer necessary; the elasticity of the main structure members will suffice. On the whole, engineering structures will tend to become more like biological ones in which fairly large extensions are acceptable, more especially they will tend to resemble the smaller animals such as insects, where stresses due to weight are less important than stresses due to other forces. With lighter, stronger and more flexible structures the weight of the structure itself, which in most cases is a very substantial part of the stress, will become relatively *unimportant*. The world of the future may be expected to look more ethereal, more like fairyland, than the world of the present or of the past.

Gothic architecture owes its character mostly to the fact that stone is strong in compression but weak in

chains together chemically so that the whole fibre became one gigantic molecule. A third slightly more fantastic suggestion is to use molecules of different shapes which would interlock when the fibre was stretched and refuse to slide till a chemical bond broke. Here one would have to be very careful that the interlocking did not take place in a way that threw all the force on to a few molecules like the key of a log-jam, so that when these broke the whole was freed. But the problem does not seem insoluble, so much is known of the shapes of molecules which can be tailored to suit almost any requirement. For example, molecules can be made with cavities containing inert atoms which are trapped inside like birds in cages and cannot escape though they are not held by any chemical attraction.

Granted then that materials can be made with much higher breaking stresses than any at present available, what effect will this have on manufactured objects? In the first place notice that stiffness will probably not be increased. This has at present about the theoretical value, and there is no reason to suppose it can be greatly improved. Now for many purposes, for example in machinery that must fit accurately even under stress, and in certain members of structures that are in compression, it is stiffness or rigidity that matters rather than ultimate strength. A member is made thicker and heavier not because one is afraid of its breaking but because its bending would cause undesirable effects. For these purposes increased ultimate strengths with the same moduli of rigidity are no improvement. But there are other purposes for which flexibility can be

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Gothic architecture owes its character mostly to the fact that stone is strong in compression but weak in

tension. Hence the architect had to arrange his structure so that the stone is almost always in compression. The reverse will be the case with the buildings of the future. Members in compression such as struts will be no stronger than they are today, for struts fail in practice by buckling, which depends on stiffness, not on ultimate strength. On the other hand, those parts of the structure which are in tension will be able to take advantage of the new strength. The resulting buildings may be a little like the masts and rigging of a sailing-ship, with the spaces between the structural members enclosed with a light 'cladding' of which a considerable fraction will be transparent.

CHAPTER IV

TRANSPORT AND COMMUNICATIONS

THE most serious problem in modern transport is not technological, or at least not apparently so. It is the problem of the rush-hour. A large proportion of modern men, and a considerable if smaller proportion of modern women, spend 10 per cent to 20 per cent of their waking life being conveyed backwards and forwards between where they live and where they work. It is probably the greatest inefficiency of our civilization and the loss in working time or happiness (which you call it depends on whether you count travelling time as work or leisure) must much exceed that caused by illness in the age-groups concerned, and these, of course, are the most important producers of wealth.

There seems no obvious way of reducing this time greatly, as long as people live and work where they do, though improvements along present lines can reasonably be expected to reduce the discomfort. The dilemma is that individual transport, such as the private motor-car, takes up so much room, while public transport makes the journey a broken one, since it seldom runs from door to door. We may dismiss the private helicopter as a serious aid. Flying means difficult navigation on certain days at least. Even with all possible aids the risks of collision in dense traffic must be appreciable, and even if they can be made no

greater than on present-day roads, the result of the slightest collision, especially near landing or take-off is too serious. Flying is no job for the tired business-man. No doubt air buses and taxis will be used, and will release other routes a bit, but the saving in time is less than appears from a naïve comparison of top speeds. Time spent in waiting, getting started, and at undesired stops, adds up and greatly dilutes the benefit from extra speed when under way.

The Communication Problem

The obvious solution is to split up the big cities into reasonable units, so that a man may live ten minutes' walk from his work if he likes to live in a town, and ten minutes' car drive over a road twisty enough to preserve some of the beauties of the countryside if he wants to live in the country. This probably means units not much exceeding 50,000 in population. To arrange this is primarily a social and economic problem, but is to some extent one in the transmission of information and therefore technological. One reason why people go to big cities is because they want to share ideas. The ideas may be those provided by the brain of a great conductor, or they may be the opinions of the stock exchange on the value of securities, or anything in between. For our purposes a more important classification is the degree of multiplicity of the communication. In the case of the orchestra it may be described as single, or nearly so. The communication that matters is that from the orchestra to each individual hearer; the interaction between the hearers is secondary, except

perhaps in the case of close friends. In the case of the stock exchange the multiplicity is much greater. The fixing of prices is the result of a joint action in which any pair of individuals may take part, not to speak of larger groups. Count the number of linkages which are liable to be required. In the former case for n people you need n linkages, in the latter case if every possible pair are to communicate it comes to $\frac{1}{2}n(n-1)$, which for large n is much more, being 4,950 if n is 100 and nearly half a million if n is 1,000. In a telephone system, of course, there is one pair of wires per subscriber and the complexity is thrown on to the switching. The air of the stock exchange, if sometimes rather overcharged with sound-waves, provides a number of 'channels' in the communication engineer's sense of the term, readily switched round in a way which would require a lot of machinery if provided electrically.

Thus there are some kinds of activity in which relatively primitive communications are an adequate substitute for bodily presence, others in which the requirements are much higher. The extent to which towns can be split up will depend on what level of communication is available. Telephones are sufficiently well established for one to have a fair idea of their limits They allow a good deal of business to be carried on at a distance, but personal contact is still necessary for many things. Telephones as at present arranged are inadequate for a meeting between more than two. It would not seem difficult for a telephone company to offer facilities by which a group could hold a meeting, each sitting in his own office—provided at least that

they were content to speak one at a time! A girl in a room in the exchange could switch the wires so that the others could all hear the speaker of the moment and a dictaphone record could be made of each speech.

What are the further foreseeable improvements? The most obvious is television. Television is at present carried out over the æther. (I cannot, as a physicist, bring myself to write 'over the air'.) This has very serious limitations and perhaps a short digression on the elements of communication theory may be forgiven me.

The simplest piece of information one can convey is yes or no to a predetermined question, e.g. has a named horse won or lost. In communication theory this is known (appropriately) as a 'bit' (actually this is short for '*binary digit*'); it might, for example, be represented on the Morse code, by a long or a short, by shaking or nodding the head, by hoisting or not hoisting a flag at a prearranged time, by a bonfire or its absence. But suppose you want to know more, say for example to tell a friend *who* has won the race when you and he both have a list of the horses. If you had access to a telegraph you might send the name by Morse, which would involve a certain number of dots and dashes, but if you were charged heavily for every dot and dash you might try to get a special code. Or perhaps the news must be signalled by lighting or not lighting signal fires at a number of distinguishable points. What is the best code you can make? What is the minimum number of points? Obviously you could assign one burning point to each horse in some agreed

order, say that on an alphabetical list, but this is wasteful in burning-points. Try this method. Suppose that there are 16 horses. Let the fire farthest to the left be lit only if the horse is in the second 8, i.e. the second half of the list. The next fire shall signal whether it is in the second half of whichever half it is in. That gets it down to one of four, repeating the process twice more gives the exact place in the list, with, in all, four fires. This is actually the best that is possible. With this rule the 9th horse would be shown by 1001, where '1' means the fire is lit and '0' means it is not.[1] Actually the same thing is done slightly differently in communication theory by writing the number as the sum of powers of two, e.g. $9 = 1 \times 2^3 + 0 \times 2^2 + 0 \times 2 + 1$ or, keeping only the numbers that are strictly necessary by 1, 0, 0, 1, as before. Four fires are still necessary. The important principle is that to convey precoded information requires a minimum number of signals depending on the number of alternatives in the code. For example, the 26 letters of the alphabet require five signals each (since 26 lies between 16 and 2×16). The Morse code appears to do it with not more than four dots or dashes for each letter, but then the letters are spaced and the space is nearly equivalent to an extra symbol

Now most of the information sent out in the world goes on waves of some kind. Speech goes as waves of

[1] If the number of horses did not divide so neatly by 2 you would need a number of fires corresponding to the next highest power of 2, i.e., three fires between 8 and 16, four fires between 16 and 32, five between 32 and 64, and so on. There would be vacant places at the end of the list with no horse These places, of course, would never be signalled.

alternating compression and rarefaction in the air, light as very short waves in the æther, radio as much longer waves, telephonic messages as electric waves in wires. There are certain general rules which govern the number of 'bits' of information which the medium between transmitter and receiver, be it air, æther, or a wire, can carry in a given time. To send a message on a wave you alter the wave in some way for a short time. We do this all the time in speech where the consonants are different ways of ending, or beginning, the vowel, but it is a little easier to follow the argument if one considers the radio of a ship sending Morse. The dot is a short train of waves, the dash a longer train. Now it is obvious that there is a limit to the shortness of a dot or dash. It cannot be much shorter than a single wave, or the receiver which is set to receive the wavelength will not recognize it as a wave at all, and will reject it as unimportant along with the other random disturbances which always occur. But even if it is several waves long the very fact that it *is* a dot or dash, in fact a signal at all, implies an interference with the regularity of the wave. This means that tuning is not exact. The signal will affect a receiver tuned to a wavelength rather different from the nominal one nearly as well as it will affect one correctly tuned. One gets what the radio engineer calls 'sidebands', regions outside the proper tuning where the signal can yet be picked up, and incidentally make a nuisance of itself to someone trying to listen on a different wave. It is interesting that this odd, and apparently not very important, phenomenon turns out to be fundamental, and leads

to a result that applies all through the theory of communications. In fact there is a limit to the number of 'bits' of information, in the above sense, which can be sent per second over a given channel for a given range of frequency. (The frequency is the number of waves, *not* signals, per second which the sender emits when working continuously or which the receiver takes in.) It also depends, as one might expect, on the amount of random disturbance present, but if this is not too large its exact amount is not very important. To carry information rapidly through a medium, whether wire or æther, one must be able to use a substantial range of frequency. It is the *range* of frequency, the sideband width, that really matters. The mean frequency can usually be adjusted, within limits, by special devices.

Now apply this to television. Suppose you want a picture of 400 elements each way, 160,000 in all. This has to be scanned twenty-five times a second to avoid bad flicks, making four million elements a second. Each element needs a signal which theoretically should be of strength exactly proportional to the light in the picture at that place. In practice something much rougher will do and we will suppose it either gets a signal or does not, i.e. is black or white. Hence a signal must last for at least one four-millionth of a second. It is not difficult to prove that whatever the original frequency of the wave, the *range* of frequency effectively occupied is about four million.[1] Now the frequency for 300-metre

[1] By an ingenious device, and at the expense of a good deal of extra complication it is possible to manage with just half this range, a method known as single sideband working. This favourable factor of two may be set against practical imperfections. A further improvement is often

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The same could be done, though more expensively and more cumbrously, by sending the signals along land-lines, either coaxial cables or some form of wave-guide. These last are circular or rectangular tubes which can carry waves of less than a certain length corresponding to their size, by a process of repeated reflection rather—to take a crude simile—as a parcel bounces down an inclined chute.

In these ways, it might be possible to arrange meetings of groups of people so that each could see and hear the speaker of the moment though each was seated in his own office. This would certainly allow a much greater degree of dispersion than is feasible at present and might tip the scales in favour of small units. I believe that there are some kinds of communication of high multiplicity for which one really needs to have the people actually together in the room, but they are the exception Big cities will still remain, but they may be reduced to a tenth their present size, always provided, of course, that the political and administrative difficulties can be met; few of those who still visit them regularly will have to do so every day.

Speed in Transport

It is a general rule, though not without its exceptions, that it requires more effort to travel a given distance fast than slow. There has been a steady increase in speed of transport during the last two centuries, which has been made possible by the availability of increased power. It is natural to suppose that this increase will continue, but it is worth considering what, if any,

waves (on the short side for ordinary radio) is just a million. Clearly we must go shorter than that. At three metres the frequency is 100 million and one might get in a fair number of channels, theoretically five between say 90 and 110 million. At such a frequency broadcast television is quite feasible as a single one-way transmission of information. But suppose you want to provide a television system like a telephone exchange where any subscriber can see any other, over the area and population of a big city. There would not nearly be room enough in the æther at this frequency. One might put up the frequency by a factor of 200 and the wavelength down to 1·5 cm. This is in the so-called K band, the shortest wavelengths used for radar in the last war. It is about the limit, for if you go any shorter the air begins to absorb seriously, not to speak of walls. This would theoretically give you 5 × 200 or 1,000 'channels', each of a width in frequency of four million over a range of ± 10 per cent in wavelength. Since these short waves are directional, and need not spread very much you could improve on this figure by 'beaming'. Fortunately the æther does not mind one signal crossing the path of another. Given very high quality technique—and we agree to allow full scope to the skill of technicians—it does not seem impossible for several hundred thousand people to see one another simultaneously over an area of say 100 miles across.

possible because in fact the 'information' is not really new each time. The *object* does *not* change twenty-five times a second, though a small part of it may. How far you can rely on this to allow you to restrict the sideband below what has been calculated depends on what you are looking at. A greyhound race would suffer more loss of precision than a person's face!

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would cross the Atlantic in an hour and get to Australia in five is probably all that is worth while—say four times the speed of sound. I think that we are not so far away from this even now. For distances under 1,000 miles something much less would do.

One ought to remember that while speeds of long-distance passenger travel have gone up greatly, the cost in terms of salaries has not come down and probably slightly gone up. For a man actually receiving £2,000 a year net (for our argument income-tax should not be considered), a return ticket to the United States by air is about one-tenth of his year's salary. Say that the return trip now absorbs four days of his time, including rests at the other end, and that he works 280 days a year; then the cost of his time to the nation is under £30. Occasionally his business is so urgent that the difference between 24 hours and say 2 hours really matters, but such cases are rare, and it does not look as if an increase in speed which would cost much more than £30 is economically justified—though it might pay as a luxury service or for mails.

But this problem of the fastest worth-while speed is complicated by technical considerations. The relation between power, which roughly means effort and cost, and the speed achieved is not a simple one, nor is it the same for all modes of transit. For air travel, for example, the speed of sound comes in as a rather sharp critical speed so that the arguments which apply below that speed are not necessarily valid above it.

One can give a crude idea of the factors determining economic flight as follows: the air through which it flies

useful limits of speed there may be, and how they are affected by physical laws.

The actual time from door to door for passengers, or from factory to warehouse for goods, depends only partly on the speed of the vehicles. Time spent in getting started and in arriving may be a large fraction of the total; it will usually be different for different modes of transport and may even reverse the apparent order of speed. It is often quicker to walk than to wait for a bus, and to go by train rather than to fly if the airfields are poorly situated. Since, on the whole, more short journeys are taken than long, public vehicles for the former will be closer spaced both in space and in time. In other words, for long journeys one must expect to have to go further to the starting-points, since there will be fewer of them, and to have to wait longer for the vehicle to start. This waiting time may, of course, not be wasted: one may have something useful to do; but everyone knows the waste of time caused by an infrequent service. The self-driven vehicle such as a motor-car has, of course, the great advantage that it avoids these 'end losses', to use a phrase from physics, but at the expense of fatigue, and the extra danger which is bound to come when an amateur replaces a professional driver.

Now it is not worth paying the cost of increased speed if the end losses account for, say, half the total time or more. There would be no object in going to Australia with half the speed of light, taking a fraction of a second, if it took half an hour to buy a ticket and get your luggage checked. In practice a speed that

lift to form the total drag. To fly steadily the pull of the propeller, or the push of the jet, must just balance this total drag. Now except near the speed of sound the drag of skin friction is nearly proportional to the density of the air and the square of the aeroplane. It is, therefore, greatest low down and at high speeds. But the drag due to the lift (i.e. the drag needed to sustain the weight) varies with density and speed in exactly the *opposite* way to the skin friction, increasing when this diminishes and diminishing when it increases. The *total* drag, as the sum of these two effects, can be shown to be least when the two drags are equal and occurs for a particular value of the quantity found by multiplying the density by the speed squared.[1] This determines the economical speed at which all long-distance flights are made. It depends on the height: the greater the height the smaller is the density of the air and the higher the economical speed. For a well designed aeroplane the total drag in this condition is about 1/16 *times* the weight. Furthermore it will not increase much for moderate variations from the best speed.

If the thrust of the engine were the same at all heights, one could go as fast as one liked by merely going higher, keeping the drag always at the economical value of 1/16 of the weight, and reducing the density so that the low density made up for the increased speed. *Unfortunately* this is not the case. In principle all engines lose thrust with increasing height, though some more than others. This loss of thrust limits the height at

[1] Speed modified by density in this way is measured by the commonest kind of air-speed indicator. It is known as the 'indicated speed'.

affects an aeroplane in four different ways, two helpful and two harmful. Air is needed to burn the fuel used in the engine, whether it be of the jet or piston type; only a rocket-driven plane, such as are some guided missiles, is immune from this need. Air is needed also to counteract gravity, in fact to make the aeroplane fly at all. The aeroplane is unique among vehicles in that it needs to move, and move fast, to sustain itself at all. It flies because its moving wings force the air downwards and by reaction are themselves forced upwards and supported. But the air that is left behind as the wing passes along has energy of motion, and to supply this energy power is needed, which, unless the aeroplane is gliding downhill, comes from the engine. Thus the lifting mechanism involves resistance, the first of the two harmful effects of the air. The second comes from the more obvious resistance which attends the motion of any solid through the air. Such resistance depends enormously on the shape, being very much less if all edges, corners and excrescences are carefully avoided as well as all abrupt curves, the surface being made to follow gentle flowing lines. This process is called 'streamlining', and the skill which the aeroplane designer of today has achieved in it is one of the two great reasons for the improvement in the performance of aeroplanes since the early days. (The other is the increased power and reliability of engines.) The resistance of a well streamlined body is a frictional drag called skin friction. When the aeroplane is flying level the lift of the wings must just balance the weight, and the skin friction adds to the resistance caused by the

To most parts of the world such a service could compete effectively with the cable or radio for messages. The problem of long-distance high-speed communication and passenger transport on the planet seems solved, or at least reduced to a question of administration to reduce the end delays.

For shorter distances these very high speeds are not worth while. Up to about 1,000 miles a subsonic jet will do all one wants. It would, of course, save end losses if these could be owner-driven, but a speed even as high as this increases navigational difficulties, greater density of traffic increases collision risks, and I doubt if many more people than do so now will care to fly their own aeroplane. It is conceivable that a system of remote control could be evolved and that one might be flown from a ground station like a kind of human guided missile. There is nothing inherently impossible in it, and it is a development in line with present fashion. Important people, and the rich, if there are any such, will no doubt have private planes with professional pilots.

Helicopters have a place for shorter distances—say 100–500 miles—but these also, as I have said, will need professional pilots and will perhaps be run rather as taxis. The motor-car will remain as the fastest transport that can go from door to door and be driven by the ordinary person. I question whether much further increase in car speed will occur. Really high speeds are much better achieved by air, and people will get tired of the long-distance driving for which increased speed might be justified. Finally, for distances from 100–1,000

which one can fly and gives what is called the 'ceiling'. Modern aeroplanes have pressurized cabins which allow them to fly near their ceiling, and they do so on long flights. Since the total weight slowly decreases as fuel is burnt the drag will also slowly decrease and the ceiling gradually rise and the speed with it.

If his engine is powerful enough to drive him up to the speed of sound the pilot will, in general, experience a great increase in drag near that speed. Above it however things settle down, and the above arguments still apply but with one important difference. Instead of the drag being 1/16 of the weight it will be at best about 1/6, and unless the aeroplane has been specially designed for flight above the speed of sound it will be very much worse still. But by using a specially designed turbo-jet or a ram-jet, which are efficient only at these very high speeds, it seems that it may not be very difficult to reach a speed of 2½ or 3 times that of sound.[1] There is another factor that helps. To produce a given thrust in a jet engine involves using an approximately constant weight of fuel per second. Hence the faster you can go at *constant thrust* the less time there will be to burn the fuel and the less will be burned. The saving in fuel is, of course, an effective increase in the load which can be carried instead.

Three times the speed of sound would make an Atlantic crossing in under 1½ hours. This is as short as is worth while. Even to the Antipodes it would only take 6 hours and further improvement seems unnecessary.

[1] In September 1954 in the U.S. the Bell 1A reached a speed of 1,650 m.p.h. or 2·3 times the speed of sound.

doubtful. The long time that goods take is in many cases much more a matter of organization than of engineering, for it greatly exceeds the actual running-time. All the same, there is always some advantage in speed, if only in increasing the amount of traffic which can be handled by a given installation, and with improvements in power one may expect that trains will reach speeds somewhat higher than those used at present.

The laws of resistance offered to a ship when driven over the surface of the water are more complicated than those that apply either to the aeroplane or to the train. The resistance can be divided into two parts. One is a 'skin friction', which is roughly proportional to the surface and roughly proportional to the square of the speed. The other is a resistance due to the waves. The waves that stream away from the bow, and the turbulence that is left in the wake of a ship carry energy in the form of moving water. This energy has to be supplied by whatever it is that drives the ship. Now, wave-making is a complicated process. At slow speeds it is small, even smaller than the resistance of 'skin friction'. But as the speed increases above a certain amount the resistance, due to the waves, increases by leaps and bounds and the power required to drive a vessel becomes prohibitively great.

The speed at which this rapid increase of resistance sets in depends upon the length of the ship. The longer the ship the faster it can be driven without producing an unreasonable amount of waves, assuming in all cases that the ship is well designed to make the resistance

miles there is a lot to be said for a train if one wants to be peaceful, and is not in a tearing hurry.

Goods transport presents quite different problems. If time is a minor consideration both land and sea transport require much less power than air. The value of D/L, as we will write the ratio of resistance to weight, for a good aeroplane is perhaps 1/16. There are similar ratios for land and sea travel, but while in the case of the aeroplane the D/L need not vary much with the speed of travel, in the case of both land and sea travel it increases quite rapidly with increasing speed. For land travel this is due partly at least to the resistance of the air becoming important at high speeds, and if the train is properly streamlined to reduce this resistance the value of D/L remains much less than that in the air for all speeds so far attempted on a railroad. In other words, rail transport is more economical of power than air transport. All the same it seems unlikely that it will develop much further in speed. Train speeds have increased surprisingly little in the last 100 years, and though they might doubtless be increased above 100 m.p.h., which is at present the practical limit, by using a wide gauge, or alternatively a monorail with gyroscopic stabilization, it seems rather doubtful whether this will in fact be done. They can never reach speeds comparable with that of a fast aeroplane, so that they cannot compete for the high-speed traffic. For goods it is a different matter, but apart from a few perishable commodities which go, and will continue to go, by aeroplane, the advantages of speed much beyond that of the present railway are somewhat

doubtful. The long time that goods take is in many cases much more a matter of organization than of engineering, for it greatly exceeds the actual running-time. All the same, there is always some advantage in speed, if only in increasing the amount of traffic which can be handled by a given installation, and with improvements in power one may expect that trains will reach speeds somewhat higher than those used at present.

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power might become, it is pretty clear that to drive a vessel of reasonable size at, say, 100 knots would be completely unpractical. Is there no way out? There are two which suggest themselves. The fast small craft of the last war, like the ordinary speed-boat of our seaside resorts, got over the difficulty of excessive wave-making by lifting themselves out of the water so that their weight is carried more as the weight of an aeroplane is carried. Of course, the medium which lifts is the water, not the air, and because of the much greater density of the water compared with air, the lifting area is smaller and can be supplied by the bottom of the boat, if this is suitably designed. Now in principle this might be applied to larger vessels at even higher speeds, but there are some serious difficulties. One is that the sea is very far from being a mathematical plane and the shock of hitting big waves at high speeds is so great that it would be difficult to make the hull strong enough. The other is a more practical one: what real use is it? Why be a hydroplane, when you can be an aeroplane? You will not get a better D/L, even if you get one as good, and the requirements of strength would make the hull unnecessarily heavy. I do not personally think that it will be found worth doing except for quite small ships.

The alternative is to copy the fishes. A submarine at depth produces practically no waves, and if it is properly designed its resistance need be very little more than 'skin friction'. One is accustomed to think of a submerged submarine as slow, as almost all submarines have been till recently. But this is because of the difficulty of getting an engine which will produce high

power and not consume oxygen. Nuclear power fills this need. The *Nautilus*, the first submarine with nuclear power, has been built in the United States and it was intended to build one here. As so often happens, a development intended for war may prove useful for peaceful purposes. Such a submarine could probably be driven at 70 or 80 knots with considerably less h.p. per ton than an Atlantic liner of the present day, provided that excrescences on the surface can be avoided. Whether any passengers would prefer the greater comfort of a large vessel to the greater speed of an aeroplane is a question of psychology, which I think must be left open. For the fast transport of goods a large submarine seems very promising. The economic speed for carrying goods is a matter of delicate balance. Increased speed requires more power, that is more expensive engines and more nuclear fuel, though this will be a minor cost. On the other hand, a fast vessel can make more trips in a year, or a month, and so earn more. A short transit-time saves interest on the value of the cargo, and for certain cargoes early delivery may be important. It also reduces the cost of wages for the trip. If the economic speed is only 10 or 15 knots, it will probably be better to keep to surface vessels, but if really high speeds are required a large submarine has great possibilities. I think we may reject the possibility of reaching high speeds by merely increasing the size of the ship, as the speeds increase rather slowly with the size, and the cost of harbours would become too serious. Furthermore, transport in very large units is inelastic and to that extent inefficient.

Nuclear Power

Apart from its special use in submarines, nuclear energy does not seem likely to make much difference to peacetime transport. Any substantial power from nuclear energy seems almost—but perhaps not quite—inevitably to involve the release of very large amounts of toxic radiation. This can be shielded-off, but it requires large masses to do it and I can see no hope of any considerable reduction in these as long as the reactor is close at hand. Hence a nuclear reactor in a *small* vehicle must require a wasteful amount of space and weight to shield it from the passengers and crew. As against this one saves in fuel, which may matter on a long trip, but it seems very doubtful if this will be worth while. The size of the earth is not large enough to make the fuel as important as that. If one had to build large liners it might be worth while, for the thickness of shield required goes up very slowly with the power—and would be somewhat reduced if the reactor could be placed a long way from anything living. Of course this does not exclude the use of nuclear energy for unmanned guided aircraft for war purposes or to carry mails.

The Germanium Transistor

A variety of minor advances in communications may be expected quite soon as the result of the discovery of the germanium transistor. This is a device using the rare metal germanium, one source of which is the deposit in the flues of coal-burning furnaces. It recalls the crystal detector of the old days of radio both in

construction and in operating principle, but with the enormous improvement that it can be made not only to rectify, but to amplify, thus acting as a triode valve. Its advantage lies in the great reduction in size and in weight that it will make possible in electronic gear. Its disadvantage is that it is not yet so free of erratic disturbance, the so-called noise, as a good valve, nor can it be made so accurately to specification, but it is a very young device and should improve. It is possible that a short-range 'walkie-talkie', light enough to be carried regularly, may in the course of a few decades replace a good deal of telephony over wires.

Long-distance Communication

Long-distance television is harder. We have seen that high frequencies are needed to transmit the wealth of information required. Unfortunately such waves are not naturally bent round the earth to any great extent so that receiver and transmitter need to be almost in sight of one another, though the fogs and dust which make the atmosphere opaque to visible light do not matter. It looks as though the link will have to be by cable or wave-guide, involving a good deal of difficult engineering when wide oceans have to be crossed. The analogous but easier problem of cable telephony has been solved and will very soon be working across the Atlantic.

So far then it seems that the problems of transport, and to some extent of communication, on this planet are not far from a practical solution and that the rate of advance will level off in the future. Our age may be

spoken of as the age at which world transport was achieved. If this seems a dull conclusion let us consider transport over much wider distances.

Leaving the Earth

The possibilities of travel in space seem at present to appeal to schoolboys more than to scientists. Space ships and Venusians have become a commonplace of adolescent life, more at home in the colourful comics than in the *Proceedings of the Royal Society*. This however is slightly deceptive. There is in fact much more money being spent on problems closely associated with that of leaving this planet than appears to the public. Large sums are being spent by the Great Powers on guided missiles; as so often happens the needs of war are the stimulus to the arts of peace. An appreciable part of the work that is being done on guided missiles is just the kind of thing that would have to be done if it were decided to make a great effort to send projectiles, with or without a crew, away from the pull of the earth's gravitation.

It follows from the principle of action and reaction that to balance or to overcome the force of gravity an aeroplane must give a downward momentum to the air through which it flies at a rate equal (in suitable units) to its weight. This it does by deflecting the air downwards by means of its wings. Every aeroplane is followed by a region of down-wash. The down-wash of the wings of an ordinary aeroplane, for example, affects considerably the behaviour of the tail. But if there is no air to push downwards, how is one to rise? The only possibility

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speed has to be paid for by a terrible sacrifice in final weight and this is all the worse because one must include in the final weight not only the pay-load but the weight of the casing, the nozzles and all the machinery which may be necessary to operate the rocket, everything in fact but the fuel which can be ejected at a high speed. The designer will do pretty well if he cuts down all these weights to 15 per cent of the original total, and even with only a miserable 5 per cent for the pay-load, this adds up to 20 per cent, leaving 80 per cent for fuel. With this proportion a rocket would reach 1·6 times the velocity at which the fuel is ejected. Clearly the prime object must be to arrange some type of fuel which shoots itself out with the greatest possible velocity.

Moreover, since we envisage a body capable of flight through regions devoid of air, the rocket must carry its oxygen with it if it needs any. In this respect it differs, to its disadvantage, from the jet engine which also derives its thrust from reaction, but gets the oxygen to burn its oil from the air through which it is passing. Obviously one needs some energetic reaction which will produce great heat and shoot the burnt products out with explosive force. But this is not all; it is not simply a question of energy. Only a part of the energy actually produced by the combustion of the fuel, whether it is a solid such as gunpowder, or a mixture of liquids such as the alcohol and liquid oxygen used in the German V2, appears as energy of motion in the blast. Considerations of the second law of thermodynamics intervene.

compatible with the law of action and reaction[1] is for the body to shoot part of itself downwards and so rise with the rest. In other words, to be a rocket.

Rockets

Before trying to describe the possibilities of space travel I must digress to explain the principles that govern rockets. They are in fact extremely simple. The upward thrust is equal to the downward momentum per second, and this downward momentum is the product of the mass ejected and the speed of ejection. Now it is obvious that there is a limit to the total amount of mass that can be ejected. Clearly it cannot exceed the original mass of the rocket and indeed must be substantially less, for we must be left with a framework and whatever counts as 'pay-load', whether this is an explosive or a chamber carrying a crew. The rocket is helped by the fact that as the material is shot backwards the rest of the rocket gets lighter. There is a simple relation between the final velocity of the rocket, the velocity of ejection, and the fraction of the mass which remains when the ejection is complete. The designer of a rocket wants his final velocity to be as large as possible and yet to retain as much as possible of the original weight as pay-load. In this respect he will have to compromise, but the nature of the mathematical relation, which is logarithmic[2], means that beyond a certain point a small increase in the final

[1] Chapter I, principle number two.

[2] The final velocity is equal to the velocity of ejection multiplied by $\log_e\left(\frac{m_0}{m}\right)$ where m_0 is the initial, and m the final mass.

speed has to be paid for by a terrible sacrifice in final weight and this is all the worse because one must include in the final weight not only the pay-load but the weight of the casing, the nozzles and all the machinery which may be necessary to operate the rocket, everything in fact but the fuel which can be ejected at a high speed. The designer will do pretty well if he cuts down all these weights to 15 per cent of the original total, and even with only a miserable 5 per cent for the pay-load, this adds up to 20 per cent, leaving 80 per cent for fuel. With this proportion a rocket would reach 1·6 times the velocity at which the fuel is ejected. Clearly the prime object must be to arrange some type of fuel which shoots itself out with the greatest possible velocity.

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The exact relation is a tolerably complicated one, but if the conditions are chosen favourably the speed of ejection of the burnt products depends mostly on two things: the temperature of burnt gas, and its molecular weight. The higher the temperature and the lower the molecular weight, the greater is the speed. Now the temperature at which one can work is limited not only, or even mainly, by the energy available, but by the risk of melting the container and jet. In the V2 for example, it was necessary to dilute the alcohol with water to prevent this happening. By employing tricks of cooling it is possible indeed to use a flame considerably hotter than the normal melting-point of the metal of which the rocket is made. But there is a practical limit to the extent to which this can be done.

For a given chemical reaction the average molecular weight of the products is of course fixed. In the case of oxygen and alcohol the products are steam and oxides of carbon, mostly the former. The practical velocity appears to be about 2·5 kilometres per second. Fluorine and hydrogen would do considerably better, but the chemical difficulties of dealing with very corrosive fluorine and the even more unpleasant hydrofluoric acid which it would produce; and the physical difficulties of storing liquid hydrogen, are daunting. Nevertheless it may be used, in fact it possibly has already been used. The best published estimate is that it might be possible to reach a velocity of ejection of 4 kilometres per second with something like the present set-up[1]. Taking the final velocity as 1·6 times the ejecting

[1] *Interplanetary Flight*, Clarke, p 27.

velocity gives us 6·4 kilometres per second, but the speed with which such a rocket could emerge from the atmosphere would be substantially less, partly because of the resistance of the air, but more because gravity is acting during the process and slowing the rocket down. It might in fact be about 5·4.

Now how does this compare with what would be needed for a flight to the moon? The earth's atmosphere has no definite edge, but yet falls off so rapidly that it is wholly negligible at a height of a few hundred miles. The earth's gravitational attraction also diminishes with distance but much more slowly. At a height of 1,650 miles the pull is still half that on the earth and even 4,000 miles from the surface it is a quarter of the normal value. Nevertheless it does fall off, and at astronomical distances, even the moderately astronomical distance of the moon, it is almost negligible. A projectile shot from the earth at sufficient speed will escape completely and proceed on its path through space It will be deflected by other heavenly bodies, if it happens to pass near them, and in certain special and rather rare circumstances may be captured by one and become a satellite of it. The speed for this escape from the earth is 11·2 kilometres per second and the very slightly smaller speed of 11·1 would carry a projectile, if it were suitably aimed, to a point at which the attractions of the earth and the moon balance and from which it would 'fall' towards the moon. This is a good deal higher speed even than the hoped-for 5·4 kilometres, but before considering the possibilities of closing the gap there is another smaller velocity characteristic of

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it moved through, say, 1° of latitude, and so would no longer be able to bend it into a circle of radius equal to its distance from the centre of the earth. If acceleration is continued long enough, it will spiral right away from the earth and become a freely moving body.

But even this 7·9 kilometres per second is above the velocity which can be obtained with present material in the way in which we have suggested. Is there no way out of the difficulty? The first and most obvious is to use a two-stage rocket. This is in fact a small rocket riding on the back of a large one. When the large one has exhausted its fuel the small one starts up, leaving the case of the large one behind and adding its velocity to that which the large one had previously acquired. In this way one can double the velocity, but at a serious expense in pay-load. Thus if the first rocket has a pay-load of 5 per cent, which will in fact be the second rocket, and this in turn has a pay-load of 5 per cent, the original device will weigh 400 times as much as the final pay-load; a very uneconomical process, but it would enable you to land something with the speed needed to carry it in a closed orbit. Allowing for all the various kinds of inefficiencies, it would not get you quite clear of the earth's attraction. That could be done no doubt by yet another stage, multiplying the total weight for the same pay-load by yet another factor of 20 and requiring 8,000 tons to give 1 ton the freedom of space. It is doubtful if such a large rocket would be practical, though von Braun, the designer of the V2, has seriously proposed one.

There are two considerations which may help to

the earth which is of considerable interest, namely the speed with which a body would have to be shot in a horizontal direction in order to travel round the earth for ever and ever—forgetting for the moment the existence of the air and the resistance which it would impose. It is not very difficult to see how it comes about that there is such a velocity. The horizontally moving object, moving that is at right angles to the radius of the earth, will be perpetually falling and attempting to approach the earth; but the earth is, by its curvature, as perpetually receding from it and at a certain speed of the body the two curvatures will match and the body will follow the earth indefinitely round. This value at the surface of the earth is 7·9 kilometres per second[1]. At a height where the experiment becomes practical, i.e. where the resistance of the air can be neglected, the velocity becomes somewhat smaller, but if you had to do the experiment by shooting a body up from the earth and then making it bend round, the loss of velocity in leaving the earth would be greater than the difference, and you would require rather more total velocity than 7·9, though not very much. This orbital velocity represents, so to speak, a possible first stage in escape for a body moving in such an orbit. The velocity which must be added for it to escape completely is the difference between 11·2 and 7·9, i.e. 3·3 kilometres per second. If in fact such a body had some rocket power left and could accelerate, its orbit would gradually draw away from the earth in a spiral, for the attraction of the earth would have less time to act as

[1] *The orbital velocity is equal to the velocity of escape divided by $\sqrt{2}$.*

to use for our jet particles moving with the velocities which are acquired in the process of nuclear fission, or which can be manufactured, though in relatively small numbers, in the atom-smashing machines. There are very serious difficulties even here. One of them is that while from the point of view of momentum the faster one can eject particles the better, from the point of view of energy it is just the reverse. If you want to save mass and have plenty of energy you push the things out fast, while if you do not mind about the mass but care more about energy you push more mass out more slowly. Now it is true that the nuclear reaction might well supply all the energy that would be required even to accelerate the rocket by particles of the highest velocity, but it would certainly be impossible to direct this energy only in the desired direction. If a nuclear reaction were allowed to go on at the rate you would need, so much energy would be generated that the whole rocket would melt—and indeed would behave rather like an atomic bomb. There may be a way out of this difficulty. In raising the rocket from the ground to an orbit round the earth, it is necessary to do so at top speed, for gravity is acting all the time and opposing the increase in velocity. But if the rocket is raised to a height clear of the atmosphere and turned so as to be moving horizontally, gravity no longer reduces its speed, but merely bends the path round to fit the earth. In these circumstances rapid acceleration is not necessary and there seems no reason in principle why the particles should not be ejected with velocities a thousand times greater than those used at present.

resolve this difficulty, perhaps separately or perhaps in conjunction: the use of nuclear energy, and the possibility of using a space platform, orbiting around the earth in the way we have described, from which the actual voyage could start.

You will remember that the speed of ejection of the materials of the rocket on which all this depends is increased by reducing the molecular weight. Now as long as we use chemical reactions, the end-product and its molecular weight are not fully at our disposal, though naturally one chooses a reaction which gives as light a molecular weight as one can. If, however, one can supply heat by means other than chemical, one can use substances of a very low molecular weight, hydrogen or helium, and so gain a very substantial advantage. A nuclear reactor supplies energy in the form of heat and a reactor of the so-called fast kind is not necessarily a very heavy or bulky object. Theoretically, at least, there seems no reason why it should not be used to heat hydrogen up to a very high temperature. There are, however, serious practical difficulties. The plutonium or U^{235} that would be used would melt at the temperature one would need. But this does not in itself prevent the nuclear reaction from continuing. The difficulties are certainly serious, but they are probably not insuperable, and one might hope, perhaps, to reach velocities of ejection near 10 kilometres per second. With such a rocket it should be possible to reach an orbit with a single stage, even if it were not possible to escape completely.

It would be better still, of course, if it were possible

difficult to adjust the balance by a low-power leak of either sign.

Whatever method is, in fact, adopted, the slow acceleration of a rocket once it has reached an orbit outside the atmosphere seems not to conflict with any physical principle. Nuclear reactions can provide ample energy, and since it can be applied slowly there need be no difficulty about over-heating, while with such a high-speed jet the amount of actual material required is not prohibitive.

Such a rocket could cruise about the solar system and make orbits round the moon and planets. To land when it returns to earth it could have wings and gradually lose speed by the resistance exerted by the upper parts of the atmosphere, finishing its course as an ordinary glider. A landing of this kind is a manœuvre which needs judgment and accuracy. If carried out clumsily the machine may be burnt up by the heat produced by its passage through dense air. The extremely high speed acquired in approaching the earth will have to be destroyed very gradually in the low-density upper layers before the pilot dares to venture lower.

To land on the moon, still more on a planet, is a serious undertaking Unless the planet has an adequate atmosphere, which the moon certainly has not, the landing will require the use of a downward blast of rocket to check the velocity of fall; in fact the process is that of take-off reversed, as seen in a cinema film run backwards. This retardation, because it needs a large thrust, can only be done by particles of thermal velocities and will necessarily cost a lot of jettisoned material.

There are indeed serious practical difficulties. One way of making a very fast jet would be to install a machine for accelerating ions, but if it at all resembles those already in use it would be enormously heavy in proportion to the mass it ejects. Theoretically, if nuclear fission can be made to proceed on the surface only of a block of plutonium, and those fission particles that were moving outwards were allowed themselves to form the rocket jet, one could do without any other machinery. But this very simple solution seems quite impracticable because of the great discrepancies between the penetrating powers of the neutrons which are producing the reaction, and the fission particles which it is desired to use. Only a negligibly small proportion of the fission particles produced would escape as desired. A better chance would be to use the radio-active fission products, which are a by-product of nuclear energy piles and give off beta rays (fast electrons). These have a relatively long range, and if the material were spread out thin over a large surface nearly half of them could escape. Electrons are too light to form the material for an efficient jet, but it would not be very difficult to use their energy to generate an electric field which could be used to accelerate heavier-charged bodies, either atoms or clusters of atoms, which could provide the actual material of the jet. Positively-charged particles would be used so that they could compensate for the loss of the negatively-charged beta rays. The rocket must not lose or gain a net charge for any length of time, or it will build up an enormous electrical potential stopping the process; but it is not, in theory at least,

difficult to adjust the balance by a low-power leak of either sign.

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The same, of course, will be true for the take-off. Thus, to reach a planet, without atmosphere, of the size of the earth, land on it and get back would require an ability of accelerating rapidly three times that required to reach the earth's orbital velocity. That is rocketry enough to give a velocity $3 \times 7 \cdot 9 = 23 \cdot 7$ kilometres per second. The moon is very much smaller than the earth and Mars somewhat smaller. The figures for these are: moon 11·1 kilometres per second, Mars 16·5 kilometres per second. These are high figures. Still, one cannot help feeling that both can be attained by developments on the lines we have indicated. Improved materials will be an enormous help by reducing structure weights.

A project is being pressed in the United States by von Braun, the designer of the V2, of establishing a permanent satellite round the earth, which would act as a half-way stage for flights to the planets. It would have to be assembled in space from relatively small components shot up by rockets in the way that has just been described. These components would move round in similar orbits if their velocities were correctly adjusted, and it is considered that they could be directed pretty close together and finally united into a structure. This would, of course, involve men working in the vacuum in suits containing air near the normal atmospheric pressure. The design of such suits presents problems, but some have been designed to make possible the escape of pilots from aeroplanes flying at an altitude at which life would be impossible, and, though cumbrous, they seem to allow reasonable freedom of

movement. It must be remembered that once clear of the earth's atmosphere, whether in an orbit or not, there would be no sensation of weight. Nor would there be any tendency for a body, human or otherwise, accidentally detached from another body, either to move further away or to return. It is extremely doubtful what the physiological effects will be, for no one has experienced such a state for more than a very few seconds. Even a man falling in a delayed parachute drop soon goes so fast that the resistance of the air prevents his free acceleration, while once his parachute has opened and his speed has steadied, he feels his normal weight despite his downward motion. Experiments on animals carried up in rockets in the United States suggest that the effect is not serious, but here again the times were relatively small and troubles such as exaggerated sea-sickness may be one of the most serious in space navigation. If it were possible to complete von Braun's space station, it would be given a kind of artificial gravity by making it in the shape of an immense tyre and spinning it so that centrifugal force would simulate gravity and tend to drive everything inside the tyre to rest against its outer rim. It is hard to see how one could do anything satisfactory on these lines for the much smaller vessels, which alone could journey to the moon or planets.

The conception of a satellite station should not be dismissed as wholly fantastic, though it bristles with technical difficulties. What I personally regard as absurd is the emphasis von Braun lays on the satellite station as an instrument of war, to be used for observation

and presumably to direct guided missiles. Unless one country had such an enormous technical lead over the others that it would not need such an aid, I cannot see the least prospect of establishing a station that would not be destroyed almost at once by guided missiles from below, which would be far easier to construct than the station itself.

One possible difficulty of inter-planetary flight is the danger from meteorites. Meteorites even of the size of a rifle bullet are extremely rare, and if they were the only danger the space traveller would be far safer than in Piccadilly, but there are vast numbers of quite tiny meteorites of the size of a pin's head, or less, which might do serious damage to the skin of the vessel and produce leaks of the air that it must contain. It has been suggested that the danger of this could be almost eliminated by a thin outer covering, an inch or two away from the air-tight material. The meteorite would vaporize a small portion of this shield and itself as well.

It is obvious from this short account that there are many difficulties to inter-planetary travel besides the obvious one of getting off the earth, but there seems to be nothing that is really fundamental and one cannot help feeling confident that in the next 50 or 100 years the ingenuity of engineers will have overcome them.

It is another matter if one wants to get to even the nearest star, Proxima Centauri, 4·3 light years away. While nothing can go faster than light it is now possible to accelerate electrons to within a very small fraction of that speed and even protons to something quite comparable. At speeds very close indeed to that

of light odd things happen with time, and ordinary chemical and biological processes might be expected to go much more slowly[1]. To make any use of this would require a new physical discovery, for change in time-scale involves proportional change in mass as well, and therefore enormous added energy. No nuclear reaction conceived at present involves the destruction of more than one part in 130 of the reacting masses, which is what one gets when four hydrogen nuclei condense to form one of helium. To give even one-half the velocity of light requires on the most favourable calculation a mass-ratio of 83, in other words 82 parts in 83 of the original rocket must be fuel and only one part in 83 structure and pay-load, a state of things which it would be difficult to achieve even with a multi-stage rocket. But at half the velocity of light the change in time-scale is only 15 per cent and the time to Proxima Centauri and back would be $4 \cdot 3 \times 2 \times 2$ or $17 \cdot 2$ years as measured from the earth, and only $2 \cdot 6$ years less from the point of view of the crew of the rocket. This seems a small prize for all the discomfort and risk. Whatever the attractions of interstellar travel perpetual youth is hardly likely to be an important one. Apart, however, from the time it would take to get anywhere worth while, escape from the solar system is not all that difficult—not much harder than a landing and return from Mars.

[1] The bearing of the relativistic contraction of time on this problem has been questioned, since it leads to an apparent paradox, but the best opinion is that the contraction would occur and that the returning astronaut would, in fact, find that time had gone more rapidly on the earth than on his space ship.

Is there a way over the time difficulty? Perhaps, if there are such things as negative protons, and one could make and handle them in bulk—but this is not the foreseeable future. A visit to the stars is not imminent but we may well be nearer to it in time than we are to Pekin man.

CHAPTER V

METEOROLOGY

It is probably true to say that the aspect of man's environment which causes most general dissatisfaction is the climate. Hardly any people are satisfied with what nature provides. Nor are they to blame for being discontented. Quite large parts of the earth are wholly useless because of climate alone, usually because they are either too arid or too damp, too hot or too cold. Can anything be done about it? At first sight the prospects look very poor. Even the milder forces of nature are enormous. The energy release in a mild shower over a few square miles is comparable with that of one of the early atomic bombs; the energy even in a single storm must be many thousand times as great.[1] It would seem that the power of man is too feeble to achieve anything much. But this may be too pessimistic a view. There are 'trigger actions' in which a small amount of energy is amplified and produces a wholly disproportionate effect by directing other much larger sources of energy into channels they would not otherwise have reached. A match can cause a forest fire which may release quite impressive amounts of thermal energy. In fact man has undoubtedly modified the climate of certain regions—usually, unfortunately, for

[1] I am informed by Sir David Brunt that the minimum for a decent-sized depression is about 70,000 million kilowatt-hours and that the big ones may be ten times this. The smaller gives 3,000 times the energy release of an early bomb.

the worse—by his own action and that of his domestic animals on trees and other vegetation.

There are two quite separate requirements if one is to do anything useful with climate: one must find some trigger which it is possible to pull, and one must be reasonably certain where the bullet that it releases will go to. This last requires a power of prediction both of weather and of climate considerably in advance of what we have at present.

Day-to-day forecasts of weather are based partly on extrapolation—assuming, for example, that a disturbance which has been moving steadily eastwards for some days will continue to do so tomorrow—and partly on comparison with the records of the past. The forecaster is reminded of weather situations which he has experienced, and by comparing the chart of barometric pressure and wind with that of some previous occasion or occasions is led to predict the sequence of events. This method, though reasonably successful for its immediate purpose, is not well adapted to predicting the consequences of artificial changes, nor does it give much help in seeing what are the features most important in determining the climate of a particular area. In recent years it has been suggested that another approach could be made. Weather is caused by the motion of masses of air of varied temperatures and humidities. This motion is governed by the laws of Newtonian dynamics and is in theory capable of calculation. It is true that the motion of air past obstacles —the wind blowing over the earth or the waves—leads to turbulent motions in which eddies are formed of

graded sizes. The precise motion of these eddies, even if not philosophically intermediate, depends on such minute causes as to be wholly incapable of prediction. Yet modern aerodynamical theory is learning how to cope with these motions by statistical analysis, and for calculating the weather a very crude averaging might well be good enough. Apart from this, the problem of the future of any known meteorological state is a calculable one, in theory at least. The practice is another matter! One needs measurements of pressure and wind not only at the surface of the earth, but at all heights to which any appreciable part of the atmosphere reaches. Ideally, these measurements should be available from stations placed at regular intervals close together over the whole surface of the earth, or at least over an area somewhat larger than that for which a forecast is desired. It is only recently, with the invention of the *radiosonde*, that this has become even remotely possible. The *radiosonde* is a small free balloon carrying a radio set and usually other instruments. The radio set can be interrogated from the ground and can send back information from which the position of the *sonde* and the reading of some of the instruments which it carries can be found. The rate of change of position combined with the known rate of rise of the *sonde* gives the wind at the various heights.

From information such as this one can determine a kind of idealized atmosphere resembling the state of the actual one but a good deal simpler and so more amenable to calculation. Work has been done on these lines both in England and U.S.A., and the results are promising.

They are already influencing actual prediction. The calculations of changes are done stage by stage, each stage representing an hour's assumed interval. From the original distribution of winds and pressures is calculated the predicted distribution an hour later, and this in turn is used as the starting-point for the next calculation. Though in basic principle the idea is simple, it is far from simple to execute. Only some of the quantities that one would like to know are in practice available at present, and the data for wide areas are scanty: for example, data of the upper winds over the Atlantic is limited to that given by a few weather ships. It is necessary to choose methods of calculation which make the best use of what data one has and use approximate theories to fill out the gaps. About 30 million individual operations have to be performed by an electronic computer for an hour stage, and one can quite understand that the computer has to be fast even to keep up with nature outside, not to say get so far ahead as to be able to issue a useful forecast. With all the difficulties it seems probable that this is the direction in which improvements in weather prediction will be made. Improvements in computers will allow more and more complications to be included in the picture, thus improving the accuracy of the prediction. Experience will show what are the features which need detailed calculation and where a rougher estimate will serve.

But the importance of this new method is not merely that it will improve day-to-day forecasts. It gives for the first time a hope of making calculations of climate, and should make it possible to assess numerically the

factors which contribute to the climate of different regions. Once it is possible to show that observed climate can be calculated from the known distribution of land with various surfaces and of sea, and of the variation with latitude of the intensity of the sun's radiation that falls on each square mile, it becomes reasonable to hope that valid predictions can be made of the effects of changes in conditions. These changes do not always produce the effects which one might at first expect. Thus most meteorologists are of the opinion that increase of the sun's radiation might lead to an ice age. Roughly the argument is that the whole circulation of the earth's atmosphere is driven by solar radiation, that increase of the radiation would speed it up and so lead to more precipitation, a good deal of which would be at the poles in the form of snow.

Clearly no one is going to start on a programme of altering climate, which at the best is sure to be extremely expensive, without some very good evidence that the result will be beneficial.

Climate has one advantage over weather as a subject for calculation. It is within reasonable limits deterministic. Now there is reason to suppose that in some cases at least the consequence of a given weather state may depend on minute effects more detailed than are accessible to ordinary meteorological observation. The weather may be like a pencil balanced on its point, which may fall one way or the other depending on some tiny tremor. It may even be truly indeterminate in the quantum sense (p. 7), but more probably it will depend on causes too small to be measured or which themselves

are due to unpredictable events, human actions for example. Indeed it seems rather unlikely that really long-term predictions of detailed weather will ever be possible. However perfect the observation of the present state of the atmosphere and however accurate the mathematical analysis, the question whether it will rain in London on the Queen's birthday next year may be truly unanswerable. It may well depend on whether someone happens to drop a lighted cigarette in a particular patch of forest in the backwoods of Quebec. But climate is different. It has stability. Over a period of years certain average temperatures and rainfalls remain. They will fluctuate a good deal from year to year, but the average over, say, thirty years will not depend much on which spell of thirty years is chosen for the average. Over a longer term there may be changes. Analysis of pollen from peat bogs has brought evidence of appreciable and fluctuating changes in the climate of Western Europe in the last three thousand years or so, but the fluctuations are slow enough to make it meaningful to speak of 'climate'; one can average over a period long enough to smooth out the variations of individual years, but short enough for there to have been little fundamental change. It is this that one could hope to calculate.

Given the fairly large quantities of energy which are likely to be available from atomic nuclei, there are various possibilities by which one might try to change climate. One might try to flood a hollow area, in the hope that a large lake once established would prove self-perpetuating. It might be possible to break up the

Arctic ice by explosions and get it carried down south as icebergs to melt in the Atlantic—though it would not be pleasant for shipping while the process lasted. If the surface of ice can be covered with a thin layer of black material it will absorb radiation from the sun that it would otherwise reflect and much more will melt. The formation of ice appears to be a cumulative process. The more there is, the more is likely to form. On the other hand, if some changing circumstance causes a decrease in the amount of ice this decrease also is likely to be progressive At present glaciers are receding, for some unknown reason. It might not be impossible to hurry this process up, and perhaps even free Greenland of ice—though the quantities involved in this are terrifying; there is much more of it than of the floating ice and it would be harder to detach. Unfortunately, melting land ice, but not floating ice, raises the surface of the sea. The Greenland ice would flood much valuable land—certainly including Cambridge!

It might even be possible to affect the total radiation reaching the earth. Much of the sun's radiation is absorbed in the upper part of the atmosphere by relatively small amounts of certain atomic species. Some is re-radiated and of this about half will go into outer space and be lost to the earth. Certain kinds of atoms and molecules have a great power of absorbing particular wavelengths; for example, it has long been known that the small amount of ozone in the upper atmosphere absorbs a quite appreciable fraction of the sun's radiation. Recent research has suggested that minute quantities of sodium in the highest parts of

the atmosphere may be producing a significant effect. Presumably the sodium comes from the sodium chloride which is shot into the air from spray from the sea—unless indeed it has been there always. While it seems on the borderline of the impossible, it should not be entirely excluded that modifications might be made in the absorption of the solar radiation in the outermost layers of the atmosphere. It might perhaps be done by an amount of material enough to make a layer not much more than an atom thick—but even an atom over the whole earth is quite a lot and something of the order of a million tons would be needed. There does not seem to be any way at present of saying how often such a layer would need renewing. Unless it were fairly permanent the effort would be prohibitive. But, of course, all this assumes that an effective reduction in the solar radiation is considered desirable and at present he would be a bold man who would say so for certain.

In recent years serious attempts have been made to produce artificial rain. The greater part of the work has been done in the United States and Australia. In all cases the object is to induce a cloud, which would normally be carried for large distances by the wind, to deposit its moisture in a particular place. There is no idea, at least at present, of increasing the total rainfall over a very large area. All that is aimed at is a redistribution. The methods used fall into two classes according to whether the upper part of the cloud is well below freezing-point or not. In the former case, where the work is associated with the name of Irving Langmuir, the idea is to produce small crystals of ice in the part of the cloud

below freezing-point. The minute droplets of water which compose the cloud normally do not freeze, but remain as water in what is called a supercooled state. These drops of water fall so slowly through the air that a small up-current will keep them suspended. Only if they can be made to grow larger will their speed through the air increase sufficiently to carry them out through the bottom of the cloud. Now, below freezing-point ice is the stable form, and supercooled drops tend to pass over into it by evaporation and recondensation, although they are unable to do so by direct crystallization until a very low temperature is reached. Hence if small ice crystals can be introduced among the supercooled drops, the drops will tend to evaporate and the vapour will be redeposited on the ice crystals. The root idea then is to produce a sufficient number of small ice crystals well distributed through the cloud, so that the water from the supercooled droplets will re-form upon them, producing relatively large crystals of ice which can fall out through the cloud. It is possible to have too many of these ice nuclei. The whole object is to increase the size of the individual particles of water, which means, of course, greatly reducing their number. One wants to 'seed' the cloud, as the phrase goes, with just enough nuclei to tap the material of most of the suspended droplets and yet few enough for each to collect the material of a reasonable volume. This is not perhaps quite as hard as it sounds, since the falling crystals tend to be spread by the turbulence in the cloud, so that there is a fair degree of mixing.

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which is being maintained by an up-current. This carries the drops in and they grow by striking against, and coalescing with, the smaller droplets.

The assessment of experiments on these lines is no easy matter. Obviously the mere fact that a cloud which has been seeded produces rain is no proof—it might have produced rain anyhow. The test involves *a statistical comparison with the rainfalls in other* places and at other times and the possibility for argument is considerable. The United States Weather Bureau has taken a very cautious and rather sceptical attitude, and some of the claims put forward by commercial operators seem to go beyond the evidence, but Langmuir's experiments are difficult to explain away, and most people seem to believe it possible to make artificial rain by seeding with carbon dioxide or silver iodide. Bowen's experiments in Australia are also impressive—he used a hygroscopic solution. It is hard to say how far methods such as these, even if developed much further, could represent a control of climate. Would it be possible to deflect any appreciable proportion of a rainfall from one area to another? It seems too early to say. The effect is somewhat limited, for only water which is already present in the air can be made to fall even at the best, and in practice only a part of this. Nevertheless the work is only beginning and it would be rash to assign too narrow a limit to its possibilities.

But when all is said, it is probably still true that the most promising method of altering climate is biological, by growing plants in desert areas and so altering the absorption of radiation by the ground and consequently

CHAPTER VI

FOOD

THE population of the world is now in the vicinity of 2,500 million and is probably increasing by about 25 million a year, 4 million of these in India. Many writers from the time of Malthus on, have pointed out that even a small percentage increase operating by geometrical progression will in time overtake any possible supply based on an area limited by the earth. The argument is in a way a bit artificial as applied specifically to food, for, even if a man could live on air and sea-water, the same argument would show that in a not-very-distant time there would not even be standing-room on the earth. All the argument proves is that the replacement rate of a species can only differ very slightly from unity when reckoned over any long period of time

Still, at the moment, mankind is increasing quite fast and rather unevenly, so that some countries, notably India, are faced by a very serious problem indeed. What has technology to say to this? Production of food on the earth can be increased in many ways, but they fall roughly into four heads. First, one might increase the area of land admittedly suitable for cultivation by opening up backward areas. Second, one might increase the area under food crops by using land not now regarded as suitable for raising food or used for other purposes. Third, one might improve the yield per

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acre of existing land. Fourth, one might produce food chemically, either from inorganic materials or from organic materials which are more easily grown than actual foodstuffs.

Taking these in order, there are enormous tracts of potentially fertile land in the basins of the Amazon, the Orinoco and the Congo. They are still very sparsely inhabited and could support a very large population if it were prepared to live at the standard of present-day India or China. No one seems to doubt that these places can and will be developed; the question how far they can relieve the congested areas of the world is political and financial rather than technological. Technology is, of course, helping. Development by aeroplane rather than by road is already happening in Brazil. Tropical medicine makes settlement possible without fantastic loss of life. Mechanical methods of handling and moving soil greatly reduce labour. Then, too, there is a wide field for biological work in developing the best crops for moist tropical conditions. One may expect that besides the obvious rice, maize, and tapioca, novel crops will be developed, crops, perhaps, which need a good deal of processing before they are fit for food. This is one of the most promising directions for biological research.

The proportion of waste land in the world is very high. Only about 9 per cent of the land surface is actually cultivated; another 16 per cent is pasture, producing some human food but much less per acre than the arable. Some, perhaps 10 per cent of the arable, is used for non-food crops, e g. cotton. If plants

are to grow naturally there are two inescapable requirements, water, and energy from the sun. At present there is not much agriculture north of latitude 60°. In the southern hemisphere the only considerable amount of land south of this is the ice-covered Antarctica (which is ignored in the above figures). It is not at all certain that the present limit is a valid one. The radiation on a flat field per 24 hours in latitude 60° in June is actually greater that it would be on the Equator because of the greater length of the day.[1] The problem is to produce a plant which will grow and ripen quickly. The start is limited by the clearing of the cover of snow, and the autumn frosts bring the end. Very substantial advances have already been made in developing quickly-ripening wheat for this very purpose, but it seems reasonable to hope that considerable progress is still possible, nor is it certain that wheat is the best plant to grow. It might be possible to develop something quite different that would grow in higher latitudes to yield a food for men or for cattle. Modern genetics opens great possibilities. Now that Moscow has renounced the Lysenko heresy it would not be surprising if the Russians did something important on these lines If food is still seriously short sixty years hence, it is reasonable to prophesy that northern Siberia and northern Canada will be producing a substantial amount.

The areas that are desert for lack of water are a harder problem. We have considered the possibilities

[1] *Report of the National Physical Laboratory Committee on Utilisation of Solar Energy*

of controlling weather and have seen that they are difficult to predict on present knowledge. Straightforward irrigation is an obvious way of using deserts, and one that has been applied throughout recorded history. At present most of the easy places have been exploited. The large areas that are left usually have no sufficient supply of fresh water within reasonable distance. If one were seriously to contemplate, for example, irrigating the Sahara, one would have to face two problems: water and power. In very many parts of the world you find water if you go deep enough, but this water comes, of course, ultimately from rain which has fallen elsewhere and made its way under the ground. Just as there are quite definite limitations to the water that can be taken from a river, so there are to the water that can be taken from wells, though because there is an underground reserve that may represent many years' accumulations the early flow may be deceptive. It may come from capital rather than from income. In Australia, for example, the flow from the artesian wells in Queensland is diminishing and the level of the water below ground is falling.

If we trust nuclear energy to supply the power, certain areas could no doubt be irrigated from water pumped from local wells, but one suspects that these areas might not be very large. Can anything be done on a really big scale with sea-water? A rough calculation suggests that the cost of conveying enough sea-water to be equivalent to a moderate rainfall need not be prohibitive. Could the water be freshened for any reasonable cost?

In recent years a good deal of attention has been given to the problem of producing fresh from salt water. There is a variety of possible methods, but the most promising are some variants of the old-established distillation method, the use of special resins with the property of exchanging ions, and electrodialysis. In distillation the water is removed from the salt, leaving a strong brine. It takes a lot of heat, but most of this can, in theory, be recovered from the vapour by various more or less ingenious processes. For example, Claude has suggested the use of the temperature differences which exist between the surface and the depths of the sea, especially in the tropics, to work a heat engine. Such an engine would involve evaporation at low pressure as one stage, and might be made to provide both a certain amount of power and fresh water, but initial costs and depreciation are likely to be high.

The resins are promising for purifying slightly brackish water, but all the salt removed from the water clings to the resins, which have to be regenerated by treatment with acids and alkalis. In dealing with sea-water the quantity of salt would probably be prohibitive. In the electrodialysis process the ions into which the salts are dissociated by being in solution, and which are electrically-charged atoms, are pulled across a stream of sea-water by electric forces and sent through permeable membranes into a 'rinsing' stream which carries them away. Membranes can now be made so as to be permeable only to ions of one electric sign (positive or negative), and this greatly increases the efficiency of the process. Even so all these processes are too expensive at

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always be supplied from the soil as must a number of so-called 'trace' elements whose necessity in very small quantities has been established in recent years. Fortunately there are large mineral deposits rich in phosphorus and sulphur and these are not likely to run out for a considerable time. Nitrates are already made extensively from the air—it is just a question of power. It would not seem impossible to condition some at least of the soil which is now rejected and make it useful. Some soil is too acid, but fortunately limestone is common, though the cost of liming is high. However, this is the kind of process which improving methods of handling in bulk will make progressively easier. In many cases the trouble is that the soil has the wrong texture to retain moisture and yet allow sufficient flow for the roots to draw nutrition from the salts contained in the necessary volume. Two methods of attack here seem likely, the chemical and the biological. The new organic chemical Krilium is intended not to nourish plants but to change the physical state of the soil. It acts by surface processes, and since a monomolecular layer absorbed on to a surface alters its properties, and molecules are small, a handful of material can alter a surprisingly large surface. Of course, the surface in question is not the crude surface seen by the eye but the vastly greater surface of the particles of the soil. Some rather similar process probably accounts for the often-claimed superiority of natural manure over artificial. The natural manure contains proteins which have the power of insinuating themselves between the sheets in which the atoms that make up clays are arranged, and

present to be economic. However, the theoretical energy requirement to freshen sea-water to an acceptable extent for drinking is only 0·7 kilowatt-hours per ton. It seems not impossible that an efficiency of 30 per cent might be reached, so that 2·3 kilowatt-hours would be needed. Even allowing for cost of plant and depreciation it seems reasonable to hope for a cost of a few pence per ton even at present prices for power. One would need about 2,000 tons per acre per year to give the equivalent of a 20-inch rainfall, so the cost seems getting within sight of what might be acceptable. If there were a real and continuing food shortage the thing would certainly be done unless it turned out that it was easier to modify the climate of the desert region and induce a rainfall sufficient for agriculture.

Apart from deserts there is a great deal of land in most countries which to the inexpert eye seems rejected for no very obvious reason. Even steep slopes can be made to yield crops after an initial capital cost for terracing—one has only to look at Northern Italy; the Inca civilization was founded on such methods, but they are used in few places only, and their use might be greatly extended.

Crops can, as is well known, be grown in water if this is supplied with suitable mineral salts. The soil is primarily a device for keeping the roots moist, secondly a means of feeding the plant with relatively simple inorganic compounds. Plants can get hydrogen, carbon and oxygen from air and water; some can fix their own nitrogen from the air, but most have to have it supplied as nitrate. Phosphorus and sulphur must

better off, except that one will be able to have a more varied diet by eating the cattle. As far as actual production of food is concerned, it is inefficient to grow crops for animal consumption and eat the animals. Meat has normally been a semi-luxury article of diet. Rarely, except among the Eskimos, has it been the staple food of all classes. But this inefficiency may cease to be important for one of two reasons. The animals may be able to live on food which can be grown in places which could not produce food for man, for example sheep on hill pasture, though even here they are apt to compete, and when sheep were extensively introduced into the Scottish Highlands crofts had to be abandoned to give them some high-class grazing. The other way is if it is possible to grow cattle food at a yield per acre greatly exceeding that possible for human food. Then one may have the double advantage of high-grade meat equal or greater in total food value to the cereal which could be grown on the area, and also large amounts of natural manure, which as we have said is superior in the long run to artificial fertilizer, and which should enable a higher yield to be obtained on the land still used for cereals.

Recent experiments in the U.S.A. and other countries suggest that this may be possible by growing some of the many species of algæ. The particular one chosen for the experiment is called Chlorella[1]. It grows as a green mush in water in bright sunshine. The water is supplied with the necessary inorganic constituents: nitrates, sulphates and phosphates of various kinds, and

[1] *Chlorella pyrenoidosa* is the species that has been used most.

so of breaking up the mass and exposing more surface. Krilium is the first of its kind, and it remains to be seen how effective it is, but the first word is not the last and this is a line of attack which it seems safe to predict will be extensively followed up.

The biological attack is more traditional. It is exemplified in the reclaiming of sand dunes. In principle it consists in finding something that will grow, however useless, and growing it. In the soil that this builds up some other plant can grow, until by stages the conditions for a useful crop are reached. It would seem that in the future, as genetics gets better understood and as methods of producing mutations artificially are improved, man will become less dependent on the plants nature has provided, and it will be possible to plan the reclamation of soils at present unsuitable, using a series of plants each designed and evolved for a special purpose.

It is remarkable how much greater the yield per acre of wheat is in Great Britain than in the U.S.A., Canada, or Russia. The proportion is roughly three for Great Britain against 1·5 for America and one for Russia. Partly no doubt this is because wheat in Britain is only grown on the most suitable land, but mostly it is a question of manure and artificial fertilizers. Both are used in greater quantities here than in the other countries. Artificial fertilizers are mostly a question of energy, and one can safely predict that their use will increase. Farm manure depends on having cattle food in abundance. If this has to be grown on land that would otherwise be used for wheat, one will be little

better off, except that one will be able to have a more varied diet by eating the cattle. As far as actual production of food is concerned, it is inefficient to grow crops for animal consumption and eat the animals. Meat has normally been a semi-luxury article of diet. Rarely, except among the Eskimos, has it been the staple food of all classes. But this inefficiency may cease to be important for one of two reasons. The animals may be able to live on food which can be grown in places which could not produce food for man, for example sheep on hill pasture, though even here they are apt to compete, and when sheep were extensively introduced into the Scottish Highlands crofts had to be abandoned to give them some high-class grazing. The other way is if it is possible to grow cattle food at a yield per acre greatly exceeding that possible for human food. Then one may have the double advantage of high-grade meat equal or greater in total food value to the cereal which could be grown on the area, and also large amounts of natural manure, which as we have said is superior in the long run to artificial fertilizer, and which should enable a higher yield to be obtained on the land still used for cereals.

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trace elements in solution. The sunshine produces the energy, and the carbon can come from the air in the form of carbon dioxide, but to get really high rates of growth it is necessary to supply carbon dioxide artificially either by bubbling this gas through the water or, better, by having the water in a container with a transparent top and maintaining an atmosphere above it richer in carbon dioxide than is normal air. The experiments are still at an early stage, but it is claimed that yields of 17½ tons per acre of dried Chlorella are possible. The protein content is very high, about 50 per cent, while that of wheat (which gives a yield in Britain of roughly 1 ton per acre) is only 12 per cent. While it may be doubted if this is yet a practical process, the experiments are certainly very suggestive. The yield is reasonably high, even in terms of the quanta of light absorbed per molecule of CO_2 turned into living matter. Photosyntheses, as these processes of the building up induced by light are called, are an excellent way of using solar energy. The radiation is, in a sense, at the temperature of the sun, and it is far more efficient to use it directly to induce chemical change than to try to make power by way of heat, as, for example, by boiling water and then using the steam at a relatively low temperature to generate power. In such a process the second law of thermodynamics, our principle seven, keeps the efficiency poor.

It seems probable that some simple organism of this kind grown under conditions in which the 'harvesting' can be made automatic and probably continuous, as has been shown possible, is the best way of using the

sun's radiation. We may expect that some process like this will enable mankind to have a higher proportion of animal food than most of it gets at present and at the same time increase the overall yield per acre.

All the above considers food production as tied to the surface of the land—we have been speaking of yields per acre. In the very long run I do not believe that this will be so, unless for some other reason population decreases. It will be a sad thing if all the pleasant places in the world have to be used for growing crops. Man has been an agricultural animal for less than 10,000 years, and the ancestors of most of us lived by hunting till perhaps a hundred generations ago. This is a short time in the history of a race, and probably most men's instincts for hunting are stronger than for growing things. Perhaps this is not true of women, but the men who would enjoy being ploughmen are, I suspect, fewer than those who would enjoy being gamekeepers.

With abundant energy it may not be necessary to depend only on the sun's radiation to grow our food. Indeed, since intensive cropping would certainly require large supplies of synthetic nitrate, the power required to make the food directly may not be so very much more. We already have an example of the upgrading of foodstuffs by chemical means in the manufacture of margarine. Fats of a poor quality have been made in Germany[1] by a completely synthetic process. Hydrocarbons derived from coal by the Fischer-Tropsch process were oxidized to fatty acids which were combined

[1] *Food and the Future*, Williams, Soc. Chem. Ind.

with glycerine, which can itself be made synthetically. If it is objected that the coal was once organic material the answer is that all trace of organization is destroyed in turning it into hydrocarbons; inorganic carbon would have done just as well as the coal. These fats had certain peculiarities which may have made them less suitable as food, but they could have been made normal at extra cost. From the long-term point of view it is pretty clear that the synthesis of fats is mostly a question of economics.

Sugars have proved difficult to synthesize, but there can be little doubt that it could be done at a price. Sugar is cheap however, and it is unlikely that such a process would pay.

Fats and sugars are among the chemically simple foods. It would be quite another matter to synthesize a piece of beefsteak which depends for its taste not merely on its chemical composition, though this is complicated enough, but on its structure and texture. It will be a very long time indeed, if ever, before certain human foods are made from the elements. I believe that one stage will be an increased production of animals for food, the animals themselves being fed partly on high-yielding organisms like Chlorella, partly on compounds directly synthesized in factories. In some cases the synthesis may not be a complete one; instead of starting from nitrogen and carbon dioxide it might pay to grow, for example, wood and use this as a starting-point for the synthesis. It is quite likely that some of the chemistry will be best done by organisms. We owe alcohol and leavened bread to the use made by early

man of biological accidents; with improving biological knowledge it ought to be possible to breed organisms to carry out a great variety of similar changes.

Yeasts have recently been grown directly for food.[1] They do not need sunshine and derive this energy from the chemical energy of their 'food', which in certain experiments has been the waste sulphite liquor from wood-pulp manufacture, and in others molasses, with some added chemicals. By varying the 'food' it is possible to get a product rich in protein or rich in fat as desired. Though these processes involve growing living matter the whole set-up is much more like a factory than a farm. For one thing, it is indoors. These processes are on the verge of being economic, but depend on having a cheap waste product to feed the yeast, of which several varieties have been tried.

It is rare in technical progress for any one line completely to supplant another Probably all methods of food production will be used. If a taste for mushrooms persists—as it surely will—it is likely always to be easier to grow than to make them. Other foods, and I suspect an increasing proportion, will come from animals fed in the ways suggested. Yet others, including perhaps a good deal of the bulk, and many of the energy-producing foods, may be made directly or from some easily grown product.

It ought to be possible to allow much of England to return to parkland and to let the downs go back to grass Large herds of cattle, fed mostly on synthetic foods delivered automatically at distributing centres,

[1] Danckwerts and Sellers, in *Food*, January 1953.

and unused to man, will roam through the trees as they did long ago. Is it too much to hope that hunting with the bow and arrow will revive as a means of procuring food from these herds and supplying the chemical engineers who made the fodder with a spice of adventure?

CHAPTER VII

SOME APPLICATIONS OF BIOLOGY

For the past hundred years, and more, physics and chemistry have been the sciences to which people have looked for practical applications. Only through medicine has biology been decisive in influencing ordinary men's lives. It is obvious that this will change, it is indeed already doing so. The science of genetics is making it possible to improve on the rule-of-thumb methods of the stock-breeder and the gardener in the improvement of tame animals and plants. Increasing knowledge of the habits of insect pests is bringing them under control and diminishing, even if it is not often possible to prevent, the losses in plants and animals which they cause. One may expect that both these applications will be enormously extended, but they are not the only ones in sight. There is probably a very large field in the extension of the use of the more lowly organisms in industrial chemistry. It has already been suggested that it may be possible to use organic agents to concentrate rare materials in sea-water, and that yeasts may be grown as food. Recent work has emphasized the important part bacteria often play in corrosion, for instance the sulphur-reducing bacteria which are responsible for much of the corrosion of buried iron pipes. Then, too, modern methods of disposing of sewage depend on bacterial actions which are

still not properly understood. One of the problems of civilization is how to get rid of its unwanted products, which include chemicals poisonous to fish and unpleasant to humans. There is a big field here for bacteriology. For thousands of years man has been dependent on organisms for the chemistry which gives leavened bread, alcoholic drinks and vinegar. In spite of the great advances that have been made in synthesizing very complicated organic compounds by purely chemical means, it is by no means certain that this is the best way to go about it in the long run. There is extraordinary variety in the diet and chemical products of the more lowly organisms, and they seem remarkably flexible, as might indeed be expected from the rapid succession of their generations. Within the time of an experiment they can go through thousands, each of which gives some scope for variation. I venture to predict that plants, moulds and bacteria bred for the purpose will in the long run compete successfully with the chemist in making some of the more complicated compounds.

Controlled Mutations

Inheritance is believed to be controlled by what are called 'genes'. In sexually-propagated organisms these are supplied by each parent of the new individual in approximately equal numbers. The mechanism, and indeed the nature, of these genes is still unknown, though very interesting suggestions with some experimental support have recently been made. It has, however, been established that genes are sufficiently

material to have a location in space. They are located in elongated bodies which are visible under the microscope and which are called chromosomes. The body cells of every species have a definite number of chromosomes—an even number. The reproduction cells each have half this number, so that when an egg is fertilized by the entrance into it of a spermatozoon half the chromosomes come from the spermatozoon and half were in the egg originally. A long series of experiments has shown that each chromosome contains the genes that control a number of characters in the new individual (in other words, it contains many genes) and it has been found possible in the case of the much-studied fly Drosophila to find the order in which the genes occur along the lengths of the chromosomes.

It may be that a gene is a long-chain molecule with side groups of atoms arranged in a characteristic order along the chain, with the property of being able to give rise to an indefinite number of other molecules like itself, rather in the way that a seal may make an indefinite number of impressions. But again this may be too great a simplification, or may only be true in certain cases. What matters for our purpose is that genetic changes can be produced by exposing the germ-cells to almost any kind of ionizing radiation; X-rays, high-speed electrons, neutrons, alpha particles from radium, all seem to produce much the same kind of effects. It is reasonable to suppose that they alter some critical molecule or molecules, either directly by knocking off electrons (ionization), and so causing a change in the structure, or indirectly by ionizing the

still not properly understood. One of the problems of civilization is how to get rid of its unwanted products, which include chemicals poisonous to fish and unpleasant to humans. There is a big field here for bacteriology. For thousands of years man has been dependent on organisms for the chemistry which gives leavened bread, alcoholic drinks and vinegar. In spite of the great advances that have been made in synthesizing very complicated organic compounds by purely chemical means, it is by no means certain that this is the best way to go about it in the long run. There is extraordinary variety in the diet and chemical products of the more lowly organisms, and they seem remarkably flexible, as might indeed be expected from the rapid succession of their generations. Within the time of an experiment they can go through thousands, each of which gives some scope for variation. I venture to predict that plants, moulds and bacteria bred for the purpose will in the long run compete successfully with the chemist in making some of the more complicated compounds.

Controlled Mutations

Inheritance is believed to be controlled by what are called 'genes'. In sexually-propagated organisms these are supplied by each parent of the new individual in approximately equal numbers. The mechanism, and indeed the nature, of these genes is still unknown, though very interesting suggestions with some experimental support have recently been made. It has, however, been established that genes are sufficiently

combinations than on using the naturally occurring mutations, though no doubt these latter often help. It seems likely that in the future more use will be made of mutations deliberately induced. In this connection I can't help feeling that the highly developed methods of what are called electron optics may be of great service. Fast electrons can be deflected and focused like rays of light, and indeed the analogy is a very close one, for electrons, like light, have wave properties. In electron microscopes beams of electrons are bent and focused to give very highly magnified images of objects through which they have passed. They surpass optical microscopes in resolving power, that is in their power to separate fine details in the specimen examined. Already the distance that can be resolved is much less than the size of a large molecule and only two or three times the diameter of the ordinary atoms that form living matter. Now the same lenses that form a vastly magnified image of an object can produce in reverse an equally strongly diminished image of an electron source, can concentrate, that is to say, an electron beam on a region comparable in size with that which could be resolved if the lenses were used as a microscope. If now such a beam is directed at a particular chromosome, or even a particular part of a chromosome, in a germ-cell, and turned on for the very short exposure which might be expected to produce a genetic effect, it seems possible that this could be controlled and that only one or two genes would be affected, and a mutation could be produced in them and in them only. No doubt, even so, most of the mutations would be harmful, but you

water near by and producing an increased concentration of electrically-charged hydrogen atoms and hydroxyl. These genetic changes are called mutations, and are inherited according to the normal laws of inheritance as first enunciated by Mendel. The great majority of mutations so produced are harmful, often to the extent of making it impossible for the creature to grow to maturity. This is hardly surprising. The mechanism, whatever it may be, which allows a complicated organism to develop from a fertilized egg is certainly a delicate one, and one is not likely to improve it by knocking pieces out at random. To take a rather different simile, it is like trying to improve a statue by spraying it at long range with bullets from a machine-gun. Yet a few mutations are improvements or, at least, changes which might be helpful in certain environments. All evolution is believed to be due to mutations large and small, of which the latter may be the more numerous and even in the long run the more important. Some mutations are caused in nature, as they probably are in the experiments, by the ionizing action of cosmic rays which irradiate us all, though rather weakly. It is perhaps unlikely that all mutations come in this way; there may be other and more spontaneous causes, for example, a bond holding part of the molecule together may slip of its own accord. There is, however, no evidence to suggest that mutations caused in one way are more likely to be helpful than those caused in another.

Present-day methods of breeding depend more on shuffling about existing genes so as to get favourable

combinations than on using the naturally occurring mutations, though no doubt these latter often help. It seems likely that in the future more use will be made of mutations deliberately induced. In this connection I can't help feeling that the highly developed methods of what are called electron optics may be of great service. Fast electrons can be deflected and focused like rays of light, and indeed the analogy is a very close one, for electrons, like light, have wave properties. In electron microscopes beams of electrons are bent and focused to give very highly magnified images of objects through which they have passed. They surpass optical microscopes in resolving power, that is in their power to separate fine details in the specimen examined. Already the distance that can be resolved is much less than the size of a large molecule and only two or three times the diameter of the ordinary atoms that form living matter. Now the same lenses that form a vastly magnified image of an object can produce in reverse an equally strongly diminished image of an electron source, can concentrate, that is to say, an electron beam on a region comparable in size with that which could be resolved if the lenses were used as a microscope. If now such a beam is directed at a particular chromosome, or even a particular part of a chromosome, in a germ-cell, and turned on for the very short exposure which might be expected to produce a genetic effect, it seems possible that this could be controlled and that only one or two genes would be affected, and a mutation could be produced in them and in them only. No doubt, even so, most of the mutations would be harmful, but you

would not have to grow the product for long to be able to reject the great mass of failures and concentrate on the few that looked promising. It would not be difficult to do this with plants or even perhaps with the lower animals. With placental mammals there would be more trouble. Either some means would have to be found of introducing the partly developed fœtus into the womb of a foster-mother and getting it attached there, or the fœtus would have to be grown entirely in artificial surroundings, which has not so far proved possible. Still, it does not seem out of the question. Whether it will ever be possible to direct the electrons with sufficient accuracy to produce a required mutation at will must remain a guess till one knows much more about the mechanism by which the genes work than is known at present, but even if all that is possible is the limited degree of control described above, by which one could determine which gene was altered, but not the alteration produced in it, the prospects for the improvement of species would be vastly improved. I have very little doubt that it will be possible to improve plant and animal breeding enormously, both in the speed with which new stocks can be established and in the range of variation possible. This by itself will make a great difference to agriculture and to the world's supply of food.

Domestication

It is a deserved reproach to civilization that hardly any new species has been domesticated in historic times. A possible exception is the recent success in the

Belgian Congo with African elephants, if it is true, which seems doubtful, that the elephants used by Hannibal and the Carthaginians generally were really of Indian not African origin.[1] It is difficult to believe that no other species could be usefully domesticated, and still harder when one considers the favourable changes that domestication can produce even with old-fashioned methods of breeding. Recent attempts with mink and silver fox may be the beginning of a needed reform. Even if it becomes possible to make most natural products artificially there will always be room for the natural to give variety. Silk production has become a less important industry, but the silkworm will never be entirely put out of business by mechanical extrusion. As bulk manufacture improves there will be more surplus man-power for luxuries, and the artistic possibilities of natural products will secure a demand.

Even with food one feels something could be done. Beef, mutton, pork, is a narrow range. Surely some enterprising company or country should find it worth while to popularize antelope or bear. It has been seriously proposed to exterminate game in Africa because of tsetse fly; it would be a disgraceful act. Man should keep out of the danger area till he has learnt enough to deal with the fly, or with the parasitic trypanosomes which it carries and which in turn carry disease. By then he will have learnt how to make use of the game,

[1] It seems from a study by Sir William Gowers (*African Affairs*, 47, p. 173, 1948) that the Carthaginian elephants and those of the Ptolemies were African, but of the relatively small 'forest' race. The Belgians also have had their main success with this race and have found the large 'bush' race much less tractable. So we have made no advance after all!

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if not commercially at least as an important element of culture.

On the whole the present age is one in which the use of animals for purposes other than food is diminishing. The horse is obsolete in the most civilized countries except for pleasure and sport; it is doubtful if wool will retain its importance as a clothing material for more than a few decades, though it will no doubt always be used for a few purposes. Even the elephant may survive in captivity more because it is picturesque than because it is useful. But are there no other possible applications? I believe that insufficient attention has been paid to the hand. The monkey's hand, though not as good as ours, is a remarkable instrument, especially when considered in connection with its eye and brain. Think what a lot of electronics it would take to make a machine capable, for example, of picking an orange from a tree without wrecking the tree. One would feel one had done pretty well to get the gear into a large lorry, and it would take kilowatts of power to operate it. The monkey does it on a weight of perhaps 40 lbs. and a daily consumption of a pound of nuts![1]

It seems to me that this combination of hand and eye connected through a moderately intelligent brain is one of the best bargains nature has to offer us. We ought to make more use of it, and I have little doubt that we shall. The picking of crops of all kinds from trees and bushes—fruit and cotton are obvious examples—are tasks which use up a lot of human effort, which

[1] One enterprising botanist, Dr Corner, has succeeded in training monkeys to collect flowers from high trees in the Malayan forests.

are decidedly difficult to do by machine yet which do not really require the full human faculties. These are perhaps not the only tasks of this kind. Certainly there are any number of factory operations which do not exercise the full human faculties, but operations in factories are under close control in a way that operations on growing plants are not. It will probably be possible to arrange these dull factory jobs so that they can be done mechanically. The photo-electric cell provides a mechanized 'eye' which is adequate for many manufacturing purposes, when only one kind of object has to be examined, and that in a particular way. Nature scores on flexibility of operation, machines on accuracy of repetition. Yet one may suspect that there exists a proportion of factory operations, even if perhaps a small one, which are suitable for trained monkeys.

It will be an interesting profession, breeding and training these creatures. With advancing knowledge of genetics very large modifications in the wild species can no doubt be made. Even the old methods were pretty good; look at the variety of dogs that have been bred. One may hope for improvements in two main ways, better hands and greater docility. Later on there may come a demand for greater intelligence, and the possibilities here are intriguing!

Population

One of the hardest things possible to predict is the course of population. Almost all the careful attempts made in the last hundred years to predict how the population of Europe and the United States would

change have proved badly wrong, though censuses are detailed and the initial data good.

In the past, population has on the whole increased, but there is evidence for periods during which it has been stationary for centuries—for example for about the first thousand years of our era. One could explain a good deal on political grounds if one were sure that the political changes were not rather the consequences of changes in population than their cause. Even so, it is odd that the same pause in the increase of population seems to have happened simultaneously in Europe and in China though there was then very little connection between them.

Nowadays in civilized countries with good medical services the rate of increase could be enormous, but it is in fact kept down by the use of contraceptives. The controlling factors cease to be biological; population is not limited by food-supply or disease but by the wishes of the people. They may be swayed by emotional considerations as well as by economic ones, and scientific prediction becomes impossible. However, one thing seems to have been learnt, namely, that a modern government can do a great deal to control population. The population of France, almost stationary for eighty years, has since the war begun to increase quite fast under the stimulus of family allowances. It was thought that the population of Britain would begin to decline about 1950 and then go down steadily, but it is still increasing; that of the United States has taken a sudden upward swing. These two countries may only be showing a reaction from the custom of very small families

which followed the introduction of contraception and led to a big drop in the birth-rate. It seemed at one time as if the white peoples intended to extinguish themselves by reducing their families well below replacement-level, but this does not seem to be so. There is no true instinct prompting the human race to have children; its place is taken under primitive conditions by the sex instinct, and under modern conditions by a rational desire for the pleasures of a family, by public and sometimes by religious opinion, and in some countries by economic motives. The experience of the last few years appears to show that these motives combined are, or can be made, sufficiently strong to provide at least a stationary population. With a heavy level of taxation, it is not difficult to provide economic incentives for large families. But all these are matters of pyschology, for even the economic motive depends under modern conditions on the views of the government, and they are uncertain and unpredictable. One can guess perhaps that the population of civilized communities will increase (but not very fast) for the next few generations, but it is a guess. We have already discussed the provision of food for an increasing population and shown that the long-term prospects, even if there is a large increase, are pretty good. On the short-term, serious troubles are apparent, which are indeed linked with the difficult question of race or rather colour, since it is the brown men of India and Indonesia, the yellow men of China, and to a less degree, the black men of Africa who are, or probably soon will be, pressing hard on the immediately available food-supplies.

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they are not brought up together. One has only to be a member of a family even of a moderate size to know that innate differences exist even between people as close genetically as brothers and sisters. If men are born equal it is a convenient legal fiction, not a fact of experience. I do not believe any schoolmaster would ever agree that the mental capacity of all children is really the same and that the differences in ability that he perceives so clearly and so early are only the result of earlier environment. But granted, as I think one must, that heredity has a great deal to say in determining mental ability even in adults when differences have been blurred by education, that gives no proof that there is a marked difference between races.

It is perhaps worth considering the analogy of athletics. There is undoubtedly a great difference between the potential and, still more of course, the actual, achievements of different individuals in bodily activities. Yet the Olympic Games are worth holding. It is not a foregone conclusion that any nation or even group of nations will win each particular event. Such tendencies as there are in this direction are probably due as much to the way in which success breeds success, by directing attention to the particular sport and setting up a good school of training, as they are to innate differences of ability. Innate differences on a statistical scale probably exist, but they are rather small and limited to particular sports. They seem rarely to extend to an overall superiority or inferiority. If the inherited mental differences between racial groups are not greater than the athletic differences they are not of

Race

There are few people in whom the problems of race do not produce a highly emotional response. Some find it shameful to suppose that groups of men exist of markedly different inherent mental ability, others find it hard to believe that people greatly differing from their own, especially in colour, can be their equals. Partly because of this emotional atmosphere, but perhaps more because of the intrinsic difficulty of the subject, there is very little worth-while evidence to enable one to say whether the minds at birth of a sample consisting of, say, a thousand negro babies are distinguishable from those of an equal sample of English babies, and if so what the difference is. It seems certain that no individual however great can transcend his social environment to more than a certain extent. Shakespeare and Newton may fairly be taken to mark the limit of the possible. The thoughts and behaviour of a man are mostly determined by those of the society into which he is born. If one judges a man on the surface by his actions, his opinions, or his words, conditions are more decisive than birth. If one of our ancestors of the Stone Age came to life he would be, superficially at least, more different from his modern descendants than those descendants are among themselves. In this sense environment counts for more than heredity. It is not so certain that this holds where the differences in environment are less, for example inside a modern nation. Observation of identical twins shows that they preserve similarities in character and behaviour as marked as their physical resemblance, even though

areas and under cruel conditions. In reaction, humanitarians may insist on measures which result in a long-term deterioration of the human stock. If ever there was a case for fair and honest investigation it is here, and no price would be too high to pay.

If the scientific position is so full of doubt, the practical one is the same Will India be successful in obtaining an outlet for her vast and increasing population, or be able to grow enough to feed them until the increase can be checked by birth-control? These are really questions in psychology and practical politics and lie outside our scope. No one can tell how long the education of a vast population will take nor how the rest of the world would react to large-scale famines. Considering how primitive agriculture is in India one is inclined to believe those who say that production by known methods could be stepped up a lot. It would be worth while for the rest of the world to devote a large proportion of its scientific and technical effort to the problem if there is reasonable hope that birth-control can become effective in a generation or two. If not it might be better to let the crash come soon on the grounds that the larger the population the worse the catastrophe will be. Other places besides India have difficulties nearly as acute, but the vast scale of India puts it in a class by itself as a world problem.

Medicine

Medicine, like transport, has progressed so far in the last century that it is reasonable to sit back and think what more we really expect of it. The expectation of

major importance. But this is what one is hardly entitled to say on the basis of present evidence. Arguing *a priori* one can say on the one hand that if the process of inheritance is the same for mental and physical characters—as most people believe—there is no reason to suppose the results to be markedly different; on the other hand it could be claimed that since the brain is the part of his body in which man differs most from his remote ancestors one might expect a greater variation between the brains of separate and possibly diverging stocks than between their bodies, which had anyhow changed relatively little. It is wisest simply to admit honestly that we do not know, that equality and inequality are still both tenable hypotheses. The problem is not insoluble if honestly tackled, but it is not an easy one, especially since one cannot do the same kind of large-scale controlled experiments on humans as one can on animals.

Since social equality usually implies mixed marriages the problems of racial mixture are relevant. What effects may one expect from mixed marriages? Are some mixtures good on the whole and others bad? Or are all good, or perhaps all bad? These are very important questions. If one produces an undesirable cross in cattle it can just be allowed to die out. With humans this is hardly possible, at least without causing much suffering. One must hope that serious study on these lines will be made by people who will try to be as dispassionate as possible. The future of the human race depends on it. Prejudice against men of certain colours may lead to their being forced to live in too restricted

There does not seem to be anything in the nature of the reproduction of tissue which demands its death; cells of a chicken have been kept alive for a period far exceeding the normal life of the bird. It appears to help if they are given nutriment derived from an embryo of the species, though this nutriment is not in any sense alive. On the other hand the peculiar aberration of cells which leads to uncontrolled multiplication and is called cancer is more likely to happen in the cells of an old individual. There may be some slow progressive change in the chemistry of an individual, but it hardly looks as though it is in the nature of things. The higher animals are so complicated that what one calls old age is likely to be the result of many quite dissimilar and unconnected causes of which sometimes one predominates and sometimes another, rather than the operation of some unescapable principle of nature. If so, it may be avoidable. I believe medical research should spend increasing effort on the prevention, which at first will be postponement, of old age. This is in my opinion more important than reducing the killing diseases much further. It is no good making everyone live to ninety if the last twenty years are decrepit. When one considers the very large differences in the age at which senility sets in, it does not seem at all a hopeless job to find ways of postponing it. It means learning a lot more about physiological processes, especially the more recondite ones. In the course of this work the mystery of cancer may be solved. There has been so much work done on it with so little real result that on analogy with other problems one feels that a direct attack is unlikely

life at birth is now 63 allowing for all accidents. It is true that there are still a number of people who die before 50, but they form a small and diminishing proportion. Apart from minor ailments which cause a certain loss of working days but do not really do anybody any serious harm, the major problem is that of old age. Is the age of 70 still to be regarded as a natural limit beyond which the normal man is worked out? If so, one may reasonably ask whether one wishes to prolong the period of life beyond 70 much more than it is at present. The fairly considerable number of people who die in the sixties and later fifties represent a problem but hardly a major one.

The whole business of old age is odd and little understood. Some primitive organisms which propagate by division are immortal apart from accidents. Plants can be propagated by cuttings for long periods of time. A cutting is still a part of the original individual, and in this way the life of a plant can be prolonged if not indefinitely at least well beyond the normal span of the species. In general, plants have a definite norm of life at the end of which they die even though the environment remains favourable. Their old age, and for that matter ours also, may be a disease, for example, an accumulation of some poisonous product or the wearing out of a few special parts for which the replacement is inadequate. Since the molecules of living bodies are being replaced all the time a mere wearing-out is an insufficient explanation. It might be, however, that the control of the rebuilding is imperfect and allows changes to occur predominantly in one direction.

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CHAPTER VIII

SOME SOCIAL CONSEQUENCES

CIVILIZED mankind at present is rather like a child who has been given too many toys for its birthday. Life seems unreal and out of focus. Shall we be able to settle down or will there be a constant and bewildering succession of fresh toys? Even allowing for the disadvantage of a very large population and of the exhaustion of oil and of the easily accessible supplies of metals, it is reasonable to expect that expanding knowledge and advancing technology will allow a steadily improving standard of living. In what form will people take it; as more toys, as amusements of complexity and ingenuity still undreamed of, or perhaps by increasing leisure? If the latter, how will they spend it?

Psychology is not an exact science, and one may doubt if it can answer such a problem. Though the extrapolation of trends is an extremely dangerous method of prediction, as all scientists know, it seems about all we can do here. Even so, one must choose what seem the more fundamental trends to extrapolate. It seems to me that one tendency which may be noticed in the last few centuries is the decline in personal extravagance. Rich men have long ceased to eat and drink as much as they can afford, or even notably more than poor men. Men, though this may not be true of women, no longer show their wealth by the variety and magnificence of their clothes. In the

to succeed. Success will come, when it does, from some quite unexpected direction; some discovery in physiology will alter present ideas as to how and why cells grow and divide in the healthy body, and with the right fundamental knowledge enlightenment will come. It is only the rather easy superficial problems that can be solved by working on them directly; others depend on still undiscovered fundamental knowledge and are hopeless till this has been acquired.

Permanent youth will certainly bring its problems, and the politicians and preachers of the future may well curse the physiologists as heartily as they now do the inventors of atomic bombs. Perhaps however, indeed probably, the process of discovery will be gradual. One cause of senility after another will be found and removed, each resulting in only a minor extension of active life. One cannot help wondering what will happen if the causes are all known and found curable. There would then be no natural term of life. All death would be by accident or intent, for in a sense death by a disease which is well understood and not normally fatal is an accident as much as a death in a motor crash.

Such a state will profoundly alter men's attitude to death, and perhaps not for the better. It may make them cowardly, for there will be more to lose. Perhaps, and that is what one would hope, they will become more philosophical, willing to resign their place on earth after a long innings and make way for new life.

shut and filtering the air that is used for ventilation. Dust from fabrics can be reduced by improving the wearing properties of the fabrics, which is anyhow desirable, and there is already evidence to show that artificial fabrics can improve on the natural ones in this quality.

I do not believe that there will be an indefinite extension of the desire for mechanical entertainment. There are a few obvious possibilities still to come after colour television. One is recorded television, whereby one could put on a record of some famous company's production of *Hamlet* as one now can for a concert piece. Individual television, in which one sees the person to whom one is telephoning, is a working tool and a valuable one as we have seen in Chapter IV, though of course it has its human value as well.

Mechanization

There seems to be little limit to the extent to which production in factories can be mechanized. The first stage, which we have long passed, is to replace human muscles by power, and the control of movement that eye exerts on hand by the rigid precision of mechanism. The next stage is to take over the task of control, to replace, for example, the human watcher of instruments whose job it is to see that some process goes on in the desired way.

Cybernetics, the science of control, is called so from the Greek word for a steersman. One of the best and earliest examples, indeed, is the automatic pilot of an aeroplane It is not such a simple job as it looks; even

present generation the habit of living in large houses has almost come to an end, and though this is partly the result of taxation and lack of servants, one wonders whether many people would really like to live in Blenheim or Audley End apart from historical association, and even so would not wish them smaller.

If then we suppose this tendency to extend, we may expect a people living in houses of quite moderate size, with moderate demands for food and clothes, even perhaps for motor-cars. Since it is obvious that in any population only a minority at most can have servants, increasing general wealth will continue to be used to provide mechanical means to replace them. Improved means of preserving and pre-cooking food will make the preparing of meals easier; can anything be done to make cleaning easier? It does not seem easy to provide mechanical devices for dusting, that most futile and wearisome of occupations, but a great deal could be done to reduce the need for it. Some of this will happen automatically. If, as we suppose, most power is produced either from nuclear energy or from coal turned into oil the industrial production of solid particles in the air will become small. If cities grow smaller the density of domestic smoke will diminish. The other main sources of dust are wind-blown particles from roads and fields and the detritus of fabrics. Large amounts of wind-blown dust mean serious loss in fertility, which must and will be reduced by methods such as those that are now proving effective in reducing erosion in the United States. If necessary, dust can be prevented from entering houses by keeping windows

shut and filtering the air that is used for ventilation. Dust from fabrics can be reduced by improving the wearing properties of the fabrics, which is anyhow desirable, and there is already evidence to show that artificial fabrics can improve on the natural ones in this quality.

I do not believe that there will be an indefinite extension of the desire for mechanical entertainment. There are a few obvious possibilities still to come after colour television. One is recorded television, whereby one could put on a record of some famous company's production of *Hamlet* as one now can for a concert piece. Individual television, in which one sees the person to whom one is telephoning, is a working tool and a valuable one as we have seen in Chapter IV, though of course it has its human value as well.

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apart from the complications of three-dimensional motion, merely keeping an aeroplane, or even a ship, with its axis pointing in some assigned direction is not easy. There is a lag between the application of the rudder to correct a deviation and the response of the ship, and when the response occurs it takes the form of giving the ship a *rate* of turn. Merely putting the rudder central when the ship points as you wish it to do is not good enough. The ship will swing past the right position and require another correction backwards. It is quite possible for a steering device to produce an oscillation of increasing violence—to 'hunt' as it is called—while all the time it is trying to make the ship go straight. But the theory of such devices and of servo-mechanisms generally (as machines are called which direct rather than supply power) has been worked out and it is now possible to control the most varied kinds of process provided one has the right instruments to say what is happening and some suitable control by which the rate or direction of the process can be altered.

A still more advanced stage of mechanization is to use something like a computing machine to control the controls and change them, so that, for example, a chemical reaction can be kept cooking for a predetermined time at a given temperature and then the temperature raised or lowered or some other ingredients added. The computing machine may be made to calculate the time, which might depend, for example, on information derived from observations on the infra-red spectrum of a sample of the batch being cooked and

fed into the calculating machine by a separate channel. These processes of control could be made more reliable than human beings and probably more economical. Ideally, a manager might come down to his factory in the morning, program its work for the day in accordance with the demand for his products by punching holes with a special typewriter in cards or a strip of paper, and leave the machinery to work unattended while he gets on with his correspondence. In practice one has a long way to go before this comes true, but some big chemical works give a hint of it. It is easiest for bulk products, next for large numbers of identical small objects and hardest, probably impossible, where the product is a small number of large and complicated machines—machinery for power stations, for example.

The Future of the Stupid

From the social aspect the interest lies in the tendency for routine work to disappear. At present a large part of the population spend their time tending machines. The number of these jobs is likely to fall steadily in the most civilized communities. If a job does not require something like the full human faculties one can make a machine to do it, usually both better and cheaper. As a step to end drudgery this is clearly a gain, but it is not so clear what the people who now do these jobs will find to do. There will be a large demand for people to design machinery and perhaps an increase in the number of really skilled workmen to make experimental machines and 'one-off' jobs generally.

But this work requires very considerable intelligence. What is to happen to the really definitely stupid man, or even the man of barely average intelligence? There will not be much room for him on the farms; already mechanization is taking over there and reducing the number of men needed on the routine jobs. The same is true even in distribution. The American habit of letting customers collect their own groceries from the shelves of the store is said to lead to increased sales, so temptingly are the tins displayed. It is likely to spread to other countries and other goods. There are limits of course. Some people enjoy or need personal contacts in shopping. I cannot see it applying to hats for example; men would get discouraged, ladies would miss their fun.

The one direction in which at present there is expanding scope for employment is in paper work, and this is very sad, for it is one of the least satisfactory ways of spending one's energies. But even here there are possibilities, chiefly coming from the new calculating machines. These, both in the 'punched card' and in the digital type, are capable of replacing a great deal of administrative work, not all of it merely routine. But even with all possible mechanical helps administrative work is likely to increase.

So also, one hopes, is the work of artists. The more mechanized production becomes, the fewer hours a day will a man have to work to provide all that he is likely to need in food, clothes, housing and ordinary furniture. There will be a surplus which can be used to allow the individual to reassert himself. People will want to have

things in their houses which are different from those of their neighbours, works of craftsmanship and works of fine art. However good reproductions may become, and they will probably become indistinguishable from the originals except by scientific tests, people will want something new and something different, even if artistically inferior. There will be surplus wealth to pay artists of all kinds and they, with the rest of the craftsmen, should prosper.

But we come back to the question of what our descendants will do with the stupider people in their new world? Engineers, artists, teachers, scientists, administrators, even salesmen have a place and a good one, but these posts are not for the stupid man. He cannot plan the day's work of a complicated factory, or take a class of boys learning electronics. Perhaps truck-driving may account for a fair number, for it looks as if the advantage of sending goods in the same vehicle from door to door may outweigh the extra cost of the larger number of drivers needed, but this source of employment alone will not go far. The proportion of boys in Britain judged intelligent enough to go to a Grammar School is about 20 per cent; add to these a few, probably a very few, who may have a special ability as artists or craftsmen without ranking high in school, and one is still left with a substantial majority. Will our descendants have to preserve inefficient ways of doing things in order to keep employment for the less gifted intellectually? A wiser course would be to use some of these men and women to humanize a civilization grown too mechanical. There are plenty

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of jobs—tending the aged is one—where kindness and patience are worth more than brains. A rich State could well subsidize such work.

Unfortunately the present differential birth-rate between classes tends to a general lowering of the standard of intelligence as generation succeeds generation. The effectiveness of the educational ladder makes this more serious than it ever was. We in Britain are taking the cleverest boys of the poor classes, very efficiently selected, and putting them into positions where they are likely to have fewer children. Possibly they will have even fewer than the average of the class they have reached, for with no capital they are likely to be slightly worse off than those with whom they come to associate, of whom some at least will have a little private means. One of the easiest ways to neutralize such differences of income and appear equally well off is to have fewer children. The country is living on its capital of inheritable intelligence. Besides the bad effect of decreasing the intelligence of the country the present method has the disadvantage that if it persists for a few generations it will create a real and permanent difference between the classes, and the poorer ones will be 'lower' in a sense that was not true when the phrase was commonly used. On the other hand the nation needs intelligence now, and can hardly afford to leave clever boys in unimportant jobs merely to provide for the next generation. The obvious solution is to make it pay for skilled workmen and the professional classes to have more children and for the unskilled to have fewer. But this is politics, and the outcome is unforeseeable,

though it is safe to say that the problem from which we started of providing jobs for the less intelligent half of the community will be one of the headaches of future politicians.

A Unified World

The last century has seen the world unify in culture to a surprising extent. If the process continues for another century, and short of a cataclysm it is pretty sure to do so, the social differences between one part of the world and another, except in so far as they depend directly on climate, will be small. Presumably differences in language will persist for a long time; nationalism is still a terribly strong force, and people prefer a language which few can understand because it gives them a sense of cohesion, like a group of small boys inventing a secret code.

But if politics allow, and in the long run they probably will, one may expect large seasonal movements of people. Different parts of the earth are pleasant at different times, but an even stronger reason is the seasonal character of so much work. There is not much need to live on a wheat farm in Canada during the winter when it is all under snow As transport becomes easier people will acquire the habit of emigrating like the swallows, or the buffalo in the old days on the American plains Fewer people, perhaps, will live in the dull places at any time. If agriculture is still practised, enough people will be there for enough of the year to sow and to harvest. Perhaps a few will have to stay to tend animals. One wonders what will happen to

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based on no real evidence. Yet evidence can be got. It is perfectly possible to devise experiments on a properly statistical plan, which, like those in agriculture, can give definite results even though individual observations show discrepancies and spread over a wide range.

Take, for example, the teaching of reading. There is far less real evidence on the best method than there is on the best sort of potato to grow. Doubtless in both cases there is no quite simple answer; the one will depend on the soil and the time of year when the crop is needed, the other on the age of the child and, perhaps, whether he has a visual or auditory memory. It seems absurd and a little pathetic that it should be possible to introduce a new method—or for that matter to retain an old one—on so much poorer evidence than would be needed to satisfy a decent agricultural research station.

The educators of the men who are to take the lead in advancing science and technology face the difficulty of steadily increasing knowledge. A man must know more and more before he reaches the frontier and can break new ground There is an inevitable pressure to extend the length of university courses and to expect men to take more and longer postgraduate studies. But the human brain remains the same. It is not good for a man to spend too long on being educated and to delay beyond a certain age starting his life-work. This age varies, it is true, and is higher the abler the man is, but for very few should it extend far into the twenties. Something can be done by improving teaching, discarding the unessential and concentrating on the root ideas.

the romantic but out-of-the-way places—St Kilda or villages in the Pamirs. Perhaps they too will be inhabited for a few months in the year and abandoned for the rest.

Education

Education will be even more important and necessary than it is now, especially technical education. A larger proportion of the population will be teachers, and it may reasonably be hoped that the process of education will be more scientific. The present state of knowledge of the principles of education is a disgrace, and very little that is effective is being done to remedy it. One has only to compare the fraction of the expenditure on armaments which goes into research with the corresponding fraction in education: the former must be hundreds of times the greater[1]. Yet military men are sometimes accused of being unintellectual! Certainly research on education, if done properly, is expensive. If a new method of teaching is to be tested, the test must be on a scale large enough to average out the good and the indifferent teachers. This means that even if one is only aiming at a modest 10 per cent accuracy one must employ groups of, at the least, 150 teachers each. So often in education the spread of a new idea is determined by the accident of its inventor being personally a good teacher or not. It is too easy for a few leading men to set a fashion

[1] Figures for research expenditure on defence are not given separately, but one may guess about 5 per cent of the total defence expenditure. An enterprising industry spends about 2 per cent of its turnover, education in Britain probably spends on research not much more than 0·1 per cent of its total expenditure.

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Far more boys, for example, learn calculus at school now than did so fifty years ago, while there are still parts of school mathematics that could be cut without serious loss. But there is obviously a limit to this process.

It is inevitable that as knowledge advances the fraction that any one man can know will diminish. This is harmful in at least two ways. Since there is so much that he must know to carry on his profession there is a very strong temptation to learn little that is not directly useful. The man gets an unbalanced view of the world he lives in. People's minds tend to fall into one of two classes, the humanistic—interested mostly in people and words—and the scientific and engineering—interested mostly in things and ideas. A man naturally takes up the profession which the bent of his mind fits best and he is unlikely to take much trouble over knowledge which is neither useful to him nor particularly congenial. It is an old evil which is getting worse, and there seem only partial solutions. Those fortunate enough to go to residential universities may learn much by close association with men of other interests and other types of mind. It is to be hoped that some system of this kind will be extended in the future to an increasing proportion of the community.

The other harm comes at a later stage of specialization. Many advances in science and technology come from applying ideas or techniques in fields other than those for which they were ordinarily intended. To do so requires a width of knowledge which it is progressively harder to acquire. It may well be that this will

set the ultimate limit to scientific advance, but much can be done to retard such a disaster. In particular we have only just started systematically making new discoveries available for specialists in allied fields. This semi-popularization will have to be greatly extended. It is not an easy thing to do, and those who do it successfully deserve quite as high a place in scientific esteem as research workers. The common pitfall is to be too detailed and too inclusive It is usually better done by someone who is not a specialist in the field reported upon As science extends it will be necessary to employ in addition to these popularizers, professional liaison officers between specific fields whose duty it will be to point out where useful contact seems possible between the fields Science will have forced upon it the same kind of development that has happened to the army The soldier in the front line needs more and more auxiliaries behind him to make him effective, and the same is happening to the research worker.

Leisure and Adventure

It is reasonable to suppose that available leisure will continue to increase. But what will people do with it? Those who are so fortunate as to have a definite leaning towards music or the arts will have no problem, nor will those with strong intellectual tastes, for whom the 'world is so full of a number of things' and who retain to maturity the fresh interests of childhood But these people are now a minority of the population as a whole, and if one blames this on bad education they seem still in a minority, though perhaps not a small one,

among those well, or at least expensively, educated. *If, as I fear, it is more a matter of nature than of training* there will be many who will not wish to occupy their leisure in these ways. Will these be condemned to divide their time between super-television, the cinema, and the football match? In this country, at least, gardening has a very wide appeal. A substantial fraction of the population, perhaps even a majority of the male population, can happily spend quite a lot of time each week on a garden patch. Another group, smaller but still large, enjoys some mechanical hobby from household repairs to model railways.

The biggest unsatisfied demand is for adventure, which in Britain is expensive enough to be almost reserved for the professional and upper classes. This is the price we pay for a dense population, for most adventure needs space. It is dangerous to repress this desire or make it difficult to satisfy. Wars are caused, more than is generally admitted, by boredom, by the desire, unexpressed but for that reason all the stronger, to escape from a dull routine into exciting adventure. *One of the advantages of being able to make food in* factories is that it will release large areas of the world as playgrounds where men can follow for a time the traditional life of the hunter and fisher and regain touch with reality.

But this is not the only possible kind of adventure. I believe that space-travel will come fairly soon, and if so it will provide an outlet for communal effort like climbing Mount Everest, but on an enormously larger scale both as regards the number of people concerned

and the time the effort will last. It will give young men the feeling that they are engaged on something unique, worthy of all their efforts, demanding self-sacrifice and calling to danger, bringing out to the full the joy of fellowship in a cause.

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Experiments under local anæsthesia show that electric stimulation of certain parts of the brain produces a feeling of compulsion to move particular parts of the body. A different line of attack is the discovery of electrical rhythms in the brain which can be detected by external coils, can be amplified and analysed. In this work, with which Lord Adrian, the President of the Royal Society, has been greatly concerned, it is for the first time possible to record physical effects coming from the living human brain, which are different in kind from the normal messages along the nerves which it is the function of the brain to send out. These waves, of frequencies varying in the region of 1 to 20 cycles per second, can be detected over different parts of the head. They are not the result of thought and may be more prominent when the brain is resting; they are apparently caused by very large numbers of cells working in synchronism. It has been suggested that one of the most prominent of these waves is a scanning mechanism associated with vision, by which the brain examines in succession the impulses sent in by the different elements in the retinas of the eyes to see if there is anything of interest. When attention is directed to some particular visual object these 'A' waves cease; they are not so noticeable when the eyes are closed. Other waves seem to be associated with emotional states or their absence.

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CHAPTER IX

THOUGHT, ARTIFICIAL AND NATURAL

JUST as the early seventeenth century gave men the beginning of physical science by Galileo, Kepler and Gilbert, so our age marks the beginning of knowledge about thought. There has been a variety of approaches. Freud and Jung have produced a kind of half-science in which minds are coaxed into revealing hidden contents by their reactions to words and ideas suggested by the experimenter, or which come to them spontaneously in dreams and reveries. The method suffers from a difficulty which recalls the Heisenberg uncertainty principle in quantum mechanics. This kind of investigation necessarily involves influencing the mind to an extent comparable with what it is hoped to discover, and in consequence it is difficult to know how far what is found was really there to start with and how far it has been put in by the investigator. Yet certain discoveries have been made: for example, that things may be forgotten not for the commonplace reason that they are trivial but because they are too important or perhaps rather too highly charged with emotion.

More recently progress has been on other lines. Surgery of living brains has provided important evidence. Severing the connections of the front part of the brain makes only a minor difference to the ability to think, but can modify character and temperament.

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Still another line has been suggested by the theory of communication developed by engineers. We have already referred in Chapter IV to the possibility of measuring information numerically and calculating

the maximum amount that can be transmitted in a given time along a 'channel' of assigned range of frequencies. Closely connected with this theory is that of the digital computers, the great machines, usually electronic, which have been developed to solve by arithmetical computation very complicated mathematical problems. In such machines two kinds of 'information' have to be fed into the machine and retained until they can be used. One is a set of instructions telling the machine what to do, the other contains the numbers on which it is to operate. To take an extremely simple case the instructions might say 'add *this* number to *that* and multiply by a *third*'. The second part of the instructions would be three lists of '*this*', of '*that*', and of the '*third*'. One of the great advances in the design of digital computers is to 'code' the first part of the instructions into the same code of *numbers* as is used for the second. It is then possible to include in the instructions one which tells the machine to operate on the number representing the instructions by one of the numbers it has calculated and use the answer as a new instruction. For example, you could make the machine print the answer to the above sum if that answer happened to be even and, say, double it *before printing if it happened to be odd*. You could do this by taking the last digit of the answer, which in the 'scale of two' commonly used is zero for an even number, and one for an odd number, and adding this to *the number representing the instruction*. In the second case the answer would be different, and this difference could be coded as an order to double.

Preparing the instructions for these machines is called 'programming'. It is one of the new rising professions. There is probably at least an analogy between what goes on in a brain and in a computer. In both cases electric signals go along linear conductors, wires in the case of the computer, nerves in that of the brain. The computer has switching devices, often in the form of valves, which can be controlled by one electric impulse so as either to transmit or hold up some other impulse, and on repeated stages of this process, associated where necessary with time delays, the working of the computer depends. It is believed that the synapses in the brain, where nerves join or closely approach one another, act in some roughly similar way. From experience in the design and programming of digital computers men can see how to imitate electronically some of the simpler processes of the brain, and to build mechanical 'animals'. Such 'animals' can not only, for example, follow a signal, e.g. a light—a feat similar to the 'homing' of a guided missile—but can be made to 'learn' in the sense of developing a conditioned reflex. Thus just as Pavloff's dogs could be taught to salivate at the sound of their dinner-bell, so a mechanical animal normally attracted by a light has been 'taught' to come at the sound of a whistle. This, of course, requires not merely that the animal is provided with an 'ear' so that a sound produces a current in some part of the mechanism that controls it, but that the interconnections of the parts of the mechanism are such that a succession of sound impulses each followed by a light changes the electrical state till

the maximum amount that can be transmitted in a given time along a 'channel' of assigned range of frequencies. Closely connected with this theory is that of the digital computers, the great machines, usually electronic, which have been developed to solve by arithmetical computation very complicated mathematical problems. In such machines two kinds of 'information' have to be fed into the machine and retained until they can be used. One is a set of instructions telling the machine what to do, the other contains the numbers on which it is to operate. To take an extremely simple case the instructions might say 'add *this* number to *that* and multiply by a *third*'. The second part of the instructions would be three lists of '*this*', of '*that*', and of the '*third*'. One of the great advances in the design of digital computers is to 'code' the first part of the instructions into the same code of *numbers* as is used for the second. It is then possible to include in the instructions one which tells the machine to operate on the number representing the instructions by one of the numbers it has calculated and use the answer as a new instruction. For example, you could make the machine print the answer to the above sum if that answer happened to be even and, say, double it before printing if it happened to be odd. You could do this by taking the last digit of the answer, which in the 'scale of two' commonly used is zero for an even number, and one for an odd number, and adding this to the number representing the instruction. In the second case the answer would be different, and this difference could be coded as an order to double.

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a sound impulse produces the same effect as a light though it did not do so originally.

The Bell Telephone Laboratory has developed an 'animal' which can 'learn' its ways through a maze, 'remember' its successful method so that it can go to the centre without mistake, and even be human enough to 'forget' if left too long without practice.

It is reasonable to foresee a time when a real knowledge of the working of the brain will replace our present hesitant guesses, it is much harder to foresee the effect of this knowledge on men's lives. Speaking for myself, the result of a very superficial study has been greatly to increase my respect for humanity. This complex instrument which we all have, or all *are* if you prefer it, with its ten thousand million working parts and its countless possible interconnections, so vastly exceeds anything we are ever likely to be able to make and is so unlike the unorganized masses we physicists study, which show at best the rather banal wallpaper patterns that crystals display. The study of astronomy makes men humble. It is somehow pathetic to read the obvious pleasure with which astronomers have now proved that our sun instead of being, as at one time it seemed to be, near the centre of our galaxy, is really in a wholly undistinguished position, neither at the centre nor at the edge. Perhaps knowledge of the human brain will make men proud, or perhaps appreciation of its defects will accumulate so rapidly as to deaden our pride of possession.

Knowledge of how we feel will perhaps have more effect on action than knowledge of how we think. One

wonders whether, for example, fervent nationalism will survive even a rough knowledge in terms of electrical circuits of the process by which it has been built up. Then humour: seeing a joke is pretty obviously a matter of unblocking some circuit or feeling a group of conflicting impulses suddenly arrange themselves in a new pattern. Would it still seem funny if we knew just what the new arrangement was? I certainly hope so, and after all our pleasure in a play or a novel is not appreciably reduced by knowledge that it is fiction. It is probably the things to which men wish to attach great and fundamental importance which will fare hardest. Principles may be difficult to retain if they can be said, plausibly if inaccurately, to be 'merely' circuit diagrams, even complicated ones. This may do harm, especially to the not uncommon kind of mind which supposes that, for example, tracing man's ancestry back to lung-fish somehow makes humanity less dignified. It is very important that people who are concerned with maintaining 'values', and surely no one would admit that he is not, should be prepared for these discoveries and willing to use mental effort to find ways by which what we now feel to matter can be retained in essence though it will most likely have to be changed in form. It is surely a mistake to suppose, as many do, that science and 'values' are such different things that the one has no influence on the other. The universe that includes our perceptions and our feelings is one, and no single part can be put into a ring-fence completely isolated from all the rest. Besides this logical connection there is a psychological one. Habits of mind

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if one had even the roughest idea of what they mean in terms of circuits.

Art, religion, patriotism, humanitarianism, what will each look like when we know what circuits are excited, and in what sequence, in the brains that feel their emotions? If one may judge from the history of thought about other aspects of nature, things which now seem much on a level may be found to have widely different degrees of importance, things which seem rather simple may turn out very complex, and perhaps the really significant and important things be found among those we now think rather trivial. Consider the relation of Jove's thunderbolt to the fluttering of chaff round a piece of rubbed amber, consider how relatively easy we now find the movements of the planets and how hard it still is to understand the workings of a worm.

In all this I have tacitly assumed that there is a one-one correlation between brain and mind, that to every state or action in the brain corresponds a conscious state, or in some cases unconsciousness, and that if you think twice of the same thing, say your first remembered schoolroom, there is something common in what goes on in your brain on the two occasions which would not be found at the many other times when you are not thinking of the room. Now this may not be true. The evidence for it is very partial and rather indirect, certainly far less strong than the evidence for determinism in the world of physics before 1900. Still, nothing is known to contradict it and the only facts, if they are facts, which do not fit in with it at all well are

that are constantly used in one part of a man's life are very likely to spill over into another. For a time mental compartments may remain nearly watertight, but sooner or later—even if not till the next generation—the walls begin to leak. People's views on 'values' will be influenced by how they regard the material world. This is specially true of religion, which uses a language of symbols derived from material things and processes and from human relations. The meaning conveyed to a geneticist by the symbol of the seed which 'dies' is not the same as it was to a peasant of the Roman Empire, nor does 'father' carry quite the same emotional content to the average modern young man that it did even a hundred years ago. If the symbolism is left unchanged, the meaning of the phrases that contain it will automatically alter with time.

As knowledge of the brain advances, the study of 'values' will become possible in a new sense. Æsthetics in particular will be greatly modified. There is obviously much that is mechanical in the appreciation of the simpler forms of music, indeed the earliest conscious scientific discovery may have been that of Pythagoras relating the harmony of notes to the lengths of the strings that produce them. A full understanding of, for example, the way the brain treats rhythm, which one would think must be a relatively simple matter, would surely make quite a difference to musical theory. Then there are the obvious and fascinating problems concerned with the difference in the kind and degree of the pleasure caused by representational and non-representational art, which would be better worth discussing

a revolution in thought. The evidence is strong, but not strong enough, partly because relatively few people have worked on it. There are instances in the history of physics where good experimenters have persistently got results which have eventually been completely disproved and abandoned. I find it a bad sign that the experimenters have been forced to introduce one hypothesis after another to account for the results of rather similar experiments; true, this might be because the whole idea is so removed from our ordinary thoughts, but it disturbs me. Even if the whole thing turns out to be untrue, a lot will be learned in proving it so. If it really is true, it would not necessarily disprove the view that brain and mind have the kind of connection suggested, but it would follow that thought is free to influence brains directly, not *only* but *including* the thinker's; it would show mind as a force acting more directly than we now suppose, and one might be inclined to regard the brain as merely the shell that holds the oyster, limiting it in some respects but not in all—but what a complicated shell!

The changes that have been brought about in the beliefs of physicists by the acceptance of the quantum theory and the principle of indeterminacy (p. 7) cannot help affecting one's view of the brain. The brain is certainly a delicately poised system with working parts on the molecular scale or very little larger. It would seem a case in which the principle of indeterminacy might be effective. Quite apart from the fact that brains somehow have minds connected with them, there is therefore no certainty that a brain is

those of 'extrasensory perception'. This phrase is used now to cover what used to be called 'thought-reading': the recently claimed power of 'precognition' by which a percipient is able to name a card of a series *before* it has been turned or seen: the power of 'clairvoyance' or correct guessing when care has been taken that nobody knows the right answer, and the supposed power of 'telekinesis', that is of influencing events of a random character without the intervention of ordinary forces.

Evidence for all these effects has been collected by a number of experimenters, notably by Rhine in North Carolina and by Soal in England. Most, but not all, of it consists in the records of experiments in which people are asked to guess what is on the face of a card which they cannot see. Many of the experiments have been conducted very carefully with a variety of precautions suggested by experience, for it is easy to get false results. The evidence is quite good, good enough to produce acceptance if what is claimed were not such a fundamental upsetting of the systems of thought adopted by most moderns and especially by scientists. For it seems that the evidence for clairvoyance *is about* as good, and of the same kind, as that for thought-transference, so that it is difficult to accept the one and reject the other. The evidence for precognition and 'telekinesis' is also strong, and all three are much less easy to fit into our general scheme of thought than is thought-transference.

The importance of the subject is enormous and much *too little work is being done on it. If true it will produce*

hey think or not is perhaps mostly a matter of , though it is hard to see how a behaviourist ıy them the same status that he gives to his nd relatives, but they will certainly have an s effect on human thought. From a scientific view one of their most important uses is to test ts of hypotheses and compare them with facts. ıeories, especially in the more abstract parts of physics are just too difficult to work out in the ordinary way by mathematical analysis, but if the theory is logically sufficient it ought to be possible to work out numerical cases. In this way, the theory can be given a check. Often the work involved is far beyond what is possible for the human computer and here the machine comes in. This possibility of dealing directly with theories, even complicated ones, and putting the results down as numbers may prove in the long run comparable in its importance to science to the use of mathematics itself. Just as the introduction of mathematics into dynamics in the seventeenth century showed how worthless were the vague qualitative conceptions of the ancients, so calculating machines in the twentieth may find holes in many well established theories. There are terribly few problems in atomic physics, for example, that one can really solve completely analytically, and one is perhaps too apt to suppose that because a discrepancy lies within the wide uncertainty of the calculations it counts as an agreement.

In the more practical world, computers of various kinds are already being used as a substitute for certain kinds of clerical labour, and this trend will certainly

even effectively deterministic as a physico-chemical system. I do not venture to say that this has anything to do with free will, nor indeed do I know exactly what is meant by that phrase, but the relation between an undetermined brain and a mind may well be other than would be possible if the behaviour of the brain were determined in the same sense that the motions of the planets are.

The true fundamental relation of mind to matter is the deepest secret of the Universe. It will certainly never be solved by mere abstract thought, words spoken or written on paper. Perhaps experimental knowledge of the effect on minds of changes in the matter in the brain may help a little, not indeed to solve the problem but to limit it and make it more precise. Perhaps it will remain for ever an example of the significant but never known.

There is more hope of practical application of the new knowledge. Why, for example, does pain hurt? Even extreme pain does not necessarily do any permanent harm though it sometimes comes from bodily injuries which do. Is it possible to stop pain not by cutting the paths which lead it into the brain, or by destroying all consciousness by complete anæsthesia, but by modifying the reaction of the brain to the impulses in the pain nerves which seem to be characterized by the great irregularity in their succession. Perhaps the Indian fakirs have learned to do something of the kind. What a protection against the oppressors if pain could be conquered from within!

Let us come back to the big computing machines;

machine ought to be able to cope. It might even be able to predict panics if they come from a real instability in the situation. It will not usually be able to deal with circumstances which depend on the will of one man, a Hitler or Stalin, especially as men who achieve great power are necessarily exceptional and so their reactions cannot be predicted from an average. It is almost worse in a democracy, where both the behaviour of the leaders and their support by the masses are matters of guess-work. Economic computers would be better off with hereditary monarchs of the eighteenth-century type.

Yet there are wide fields in which machines will certainly have value. They will at least predict the effects of given small changes, e.g., of crop yield on an assumed stable state. Situations will be analysed so as to depend on a few major unpredictables and the consequences worked out in each case. If one must still guess, at least one will know what one is really guessing about.

Already Gallup polls influence politics. In human affairs predictions are both a consequence and a cause. If the results are to be published the machine must allow for this by feeding in the consequences of its own conclusions. This, while not difficult to do technically, usually tends to produce instability. But I doubt if rulers will allow people access to the results of such calculations. They will be state secrets, and the making of them a government monopoly like atomic bombs.

To deal with such a world men will need a more quantitative education. Literature in one's own and other languages should take its place with painting and

spread. Routine operations will more and more be done by machines, especially those of the kind in which information is recorded mechanically on cards. Whether this will reduce the need for clerical labour remains to be seen. So far all the improvements in administrative technique have had the effect of increasing the number of people needed in administration. Pepys ran the Royal Navy in wartime almost literally on two men and a boy, and sent ten thousand seamen to sea. The Admiralty staff in Nelson's days was minute compared with that of the last war though the number of men at sea was not very different. Of course, modern administration is far more precise and can cope with difficulties, and especially with complexities, which would have sunk our ancestors. Probably this trend will continue and the main effect of the machines will be to administer increasingly complex organizations using possibly increasing human staffs. Machines will make possible accurate quantitative planning where we now rely on experienced judgment. Lyons for example use an electronic computer for commercial clerical work of many kinds, including dealing with the orders sent to the central office by the branch tea-shops.

Machines of a very simple kind have already been made to determine the result of external changes on an assumed economic structure. They are almost certainly too simplified, and leave out too many things that matter, for their conclusions to be worth anything, except perhaps for teaching, but they are only beginning. As long as people react to changes in a foreseeable way, whether this way is rational or not, a

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The future will see, I think, men's brains released from a tangle of hindrances that come from wrongly sorted impressions or barriers that have been set up. Whether it will be done by physical action, by feeding in perhaps electrical impulses of the right kind, or more subtly by an extension to earliest youth of the methods of the psychiatrist, is anybody's guess. When brains have reached the natural limit, and probably before then, it will become possible to produce better ones by selected mutations. Most mutations are harmful, but if none improved the brain we should still be primitive primates, not to say jelly-fish, and it seems most unlikely that the limit of the possible has been reached.

There is no reason to anticipate that anything irreparable will go wrong with the earth physically for many millions of years, and are there not other planets and other stars? It is difficult to exterminate a species once well established, and man's best efforts to kill himself are unlikely to be more successful than those of the plague bacillus or the influenza virus Even with the present brains of intelligent people Man may expect a glorious future. Who will dare to set limits to what he may reach as his brain improves? This future is not foreseeable!